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A CASE HISTORY OF THE MARYSVILLE GEOTHERMAL ANOMALY FROM A NUCLEAR WASTE DISPOSAL PERSPECTIVE

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A CASE HISTORY OF THE MARYSVILLE GEOTHERMAL ANOMALY FROM A NUCLEAR WASTE DISPOSAL PERSPECTIVE

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ABSTRACT

A case history of a mild geothermal area near Marysville, Montana has been compiled in order to learn about the effects that long-term heat generated by an irradiated fuel repository might have on the surrounding rock mass. The results of geological and geophysical surveys are summarized and the hydrogeological conditions in the granite mass, as measured in a 2km deep borehole, are described. A model is proposed which accounts for the hydrothermal circulation and explains some of the geophysical observations. The implications to deep burial of nuclear wastes are discussed.

RÉSUMÉ

Afin de savoir quels sont les effets d'une chaleur prolongée qui se dégage d'un dépôt souterrain de déchets radioactifs sur les formations géologiques environnantes, une étude a été effectuée dans une région aux charactéristiques géothermiques faiblement marquées près de Marysville (Montana). Le présent document résume les résultats des recherches géologiques et décrit les conditions hydrogéologiques mesurées dans un trou de forage de 2 km de profondeur dans le massif granitique. Le modèle proposé décrit le réseau d'eaux chaudes souterraines et explique certaines observations géophysiques. La discussion porte aussi sur les répercussions de l'évacuation en profondeur des déchets radioactifs.

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A. INTRODUCTION

1. Natural Analogues

The emplacement of radioactive wastes in the earth's crust will result in heating of the host rock for long periods of time. In particular, if irradiated fuel is not reprocessed, it will contain long-lived components which will cause elevated temperatures for times in excess of 10,000 years, as illustrated in Figure 1. Therefore, an understanding of the effects of long-term heat on the integrity of the geological system and on the behaviour of groundwater is fundamental to determining the risk of deep disposal of nuclear waste.

Atomic Energy of Canada Ltd. (AECL), who has the responsibility for developing and assessing the radioactive waste disposal concept in Canada, is relying to a great extent on mathematical models to quantify repository behaviour and to assess long-term environmental safety.[2] However, it is worthwhile to consider complementary approaches, since standard engineering and scientific analyses can not be applied confidently over such long time frames nor for such intrinsically complex systems. The study of relevant geological phenomena, that is natural analogues to repository behaviour, appears particularly promising since they have acted over comparable time scales. Natural analogues also incorporate the myriad of complexities inherent in geology. In particular, physical processes which the mathematical modeller might overlook, may become apparent.

The earth's crust provides a natural laboratory where most, if not all, of the phenomena associated with a nuclear waste repository have occurred. Probably the best example of a relevant natural analogue is the nuclear reaction which took place in an uranium ore body at Oklo, Gabon 1800 million years ago.[3] Many other phenomena, when appropriately deciphered, can yield useful information. For example, metamorphic halos around granitic intrusions can provide data on the effects of heat on argillaceous backfill materials; the metamict effect in minerals can provide information on potential damage to encapsulation materials caused by the radioactivity of the waste; a study of radiometric age dating methods can yield information on radionuclide diffusion rates, and so on. This report describes a geothermal anomaly near Marysville, Montana, which is an

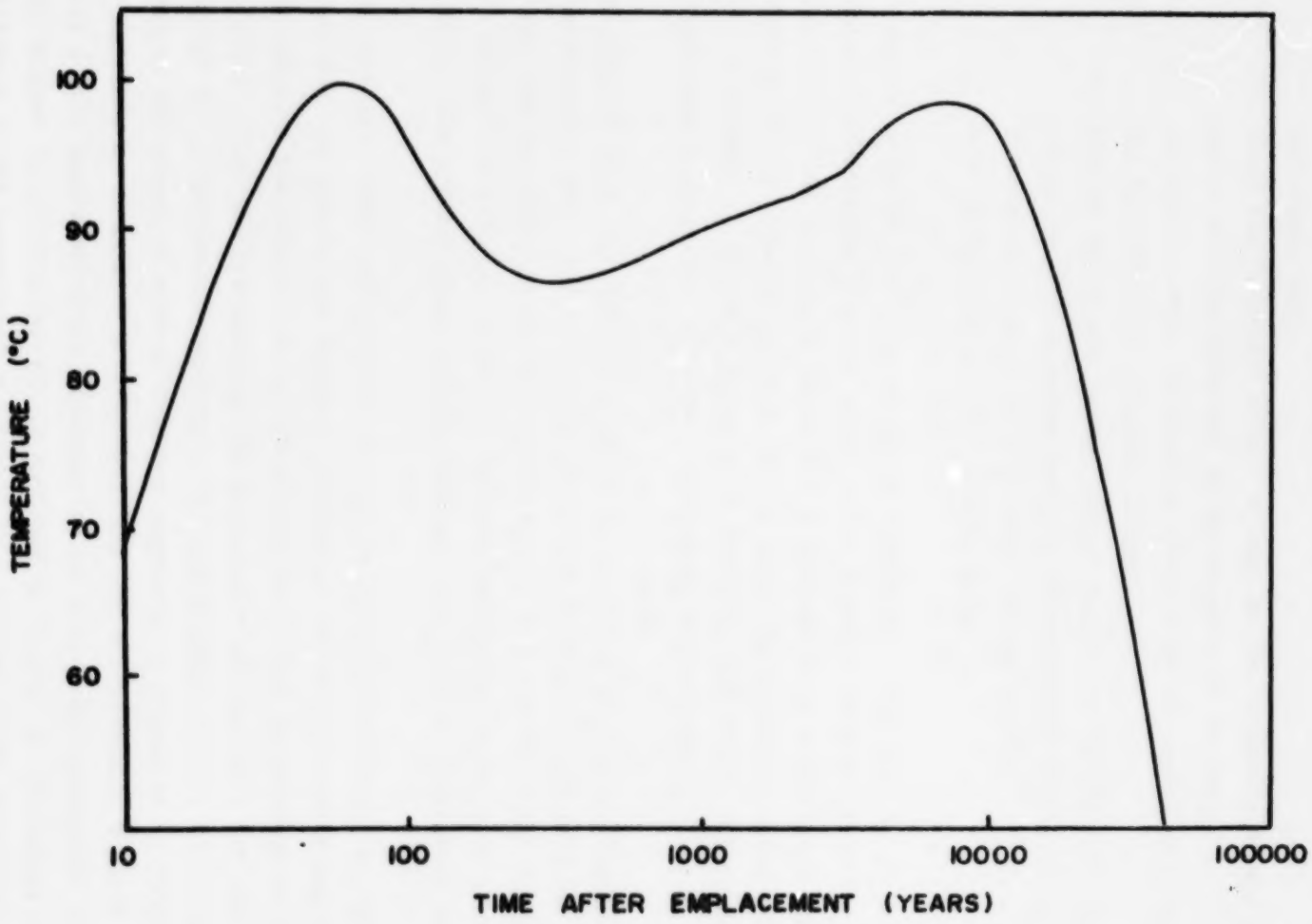

FIGURE 1-TEMPERATURE AT THE CENTRE POINT OF AN IRRADIATED FUEL REPOSITORY IN GABBRO AS A FUNCTION OF TIME[1].

analogue to the long-term thermal regime associated with a disposal repository for irradiated fuel. It provides information on the effect of heat on the rock mass and on the groundwater system.

2. The Marysville Geothermal Anomaly

The geothermal anomaly near Marysville, Montana was discovered in 1965 by Dr. David D. Blackwell of Southern Methodist University, Texas, while performing heat flow studies in the region[4]. The anomaly was unusual in that it was "blind", showing no surface manifestations such as volcanos, hotsprings, etc. Subsequently, the anomaly was extensively explored in order to assess its potential as an economic geothermal energy resource.[5,6,7] The exploration activities included geological mapping, geophysical surveys, and the drilling of a 2.1 km deep borehole. The studies revealed that the anomaly was related to a Cenozoic granite pluton, the Empire Creek stock, which intrudes metamorphosed Precambrian sediments. The deep borehole penetrated an extensive hydrothermal zone; however, temperatures were too low to support commercial energy extraction, and the project was terminated.[7]

Although unsuitable for energy exploitation, the Marysville anomaly appears well suited to be an analogue for a nuclear waste repository for the following reasons:

(a) temperatures in the ground are approximately the same as those anticipated in a repository,
(b) the anomaly is associated with a granitic pluton.

In addition, a considerable amount of information is available from the geothermal exploration. For example, the deep borehole extends to a greater depth in a pluton than will be reached by drilling in the Canadian nuclear waste disposal programs. The objectives of the present study were to investigate the geothermal anomaly from a nuclear waste disposal perspective in order to:

(a) assess the suitability of the anomaly as an analogue to an irradiated fuel repository,
(b) study the long-term effect of heat on the integrity of the geological medium and the behaviour of the groundwater regime,
(c) extract any other information which might be useful to understanding the nuclear waste disposal concept,
(d) provide the Atomic Energy Control Board with information that may be useful in writing guidelines and in evaluating applications for licenses to dispose of high-level nuclear wastes,
(e) make recommendations for further work.

It should be noted that occurrences of geothermal areas such as at Marysville, Montana (140-800mW/m^2) do not exist in the Canadian Shield. Even the background heat flow in Montana (80mW/m^2) is substantially higher than that of the Canadian Shield (50mW/m^2). Thus, in the quest for a nuclear waste disposal site in Canada, it is not a question of avoiding such areas, but rather to ensure that a repository will not create such an environment.

The present study has been carried out by reviewing available literature, by communicating with, and visiting, scientists involved in the original geothermal study, and by comparing the relevant features of a nuclear waste repository to the Marysville anomaly, as well as to other geothermal areas with granitic bodies. The present study did <u>not</u> involve field work or laboratory analysis.

The regional, local and borehole geology is reviewed in Chapter B. Chapter C describes the surface and borehole geophysical exploration which was performed and compares the predictions to the actual conditions encountered in the deep borehole. Physical hydrogeology and groundwater geochemistry are described in Chapter D. A geochemical hypothesis for hydrothermal kinetic dissolution causing the growth in size of fracture apertures is presented in Chapter E and in Appendix B. Chapter F briefly describes the environmental effects associated with a mild geothermal area. Information on three other geothermal areas which are located in granitic terrain is outlined in Chapter G. A discussion of the relevance of the geochemical hypothesis to a nuclear waste repository is presented in Chapter H, along with a summary of the main conclusions reached in this case history.

B. GEOLOGY

1. Regional Setting

The Marysville stock is part of the North American Cordilleran Orogen, a complex of genetically related structures that can be traced through Canada and the United States. The structures in the Cordilleran Orogen developed when the Pacific lithospheric plate subducted beneath the North American lithospheric plate[9] during the Laramide orogeny and in Montana consist principally of folds and thrust faults that are intersected by normal faults and intrusive and extrusive igneous rocks (Figure 2). The Marysville region lies in the Northern Rocky Mountain physiographic province.

Comtemporaneously igneous rocks such as the Boulder batholith and the associated Marysville stock of Montana intruded and metamorphosed the sedimentary rocks[10]. Subsequent to the thrusting and igneous activity, normal displacement took place on newly developed faults and on previously developed thrust faults.

The Boulder batholith is a large plutonic mass extending about 110 km from 5 km south of Helena, Montana, to 30 km south of Butte, Montana. The batholith is a composite of several magmas intruded during the Cretaceous period. Robinson et al[10] reviewed K-Ar age data which indicate the bulk of the Boulder batholith crystallized between 78 and 72 million years ago. The batholith and its satellite stocks intruded and metamorphosed sedimentary rocks that range from Precambrian (Belt series)[18] to Cretaceous (lavas and pyroclastics) in age.

Intrusion of the Boulder batholith was preceded by volcanism and was contemporaneous with the most intense folding and thrust faulting of the Laramide orogeny in Montana. Robinson et al[10] presented convincing evidence that the

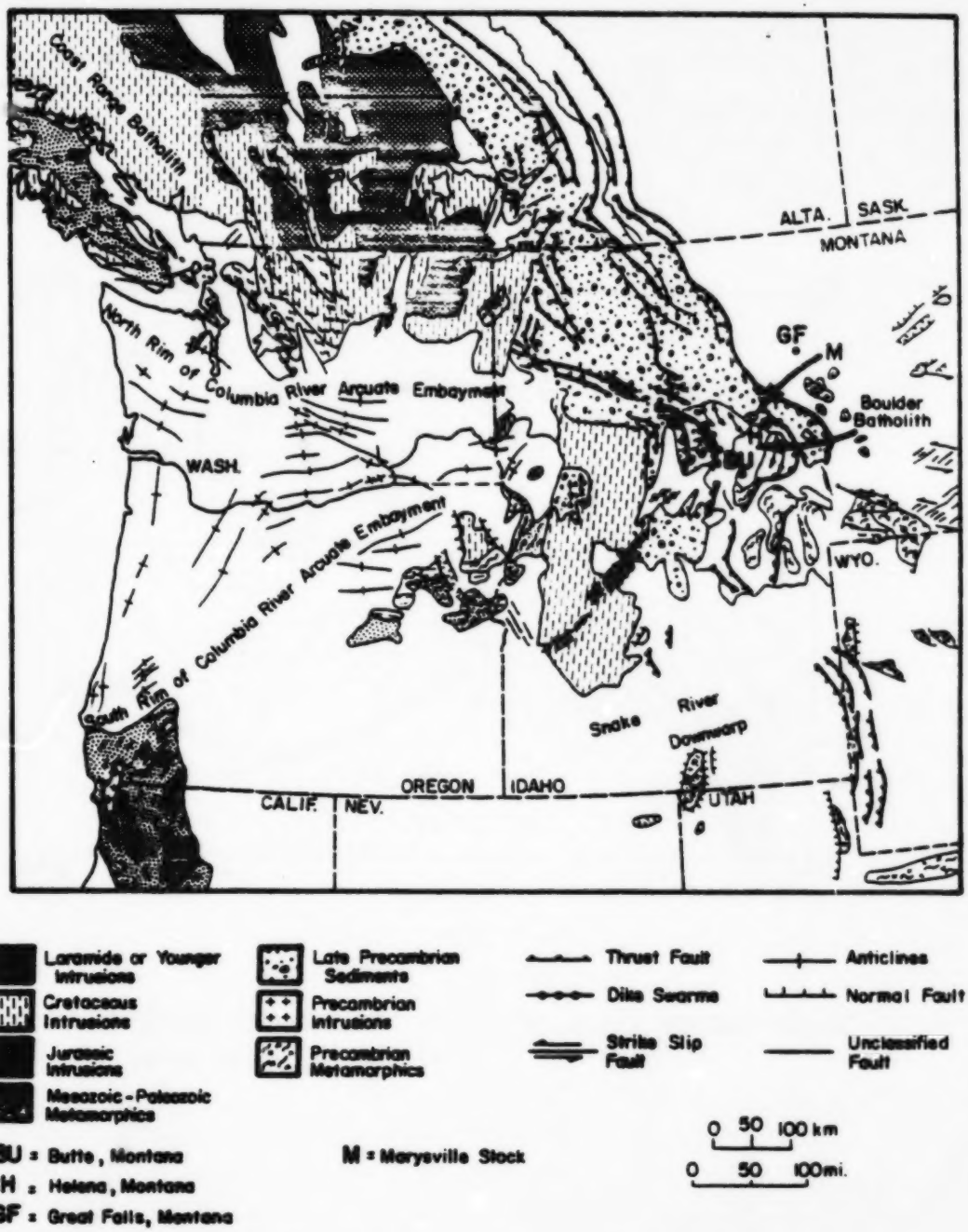

FIGURE 2-TECTONIC FRAMEWORK OF THE PACIFIC NORTHWEST[8].

batholith intruded within about 20 million years of the folding and thrusting that formed the Rocky Mountain thrust belt of Western Montana.

The Marysville stock is the best known of many stocks that surround the Boulder batholith in Montana (Figure 3). The precious metal mining district geographically associated with the Marysville stock was the principal reason for investigation of the area by the U.S. Geological Survey.[12] Continued economic interest in the mining district has supported several detailed studies of the igneous intrusions in Montana.[13,14,15,16,17]

The emplacement of the Marysville stock was an integral part of the plutonism, volcanism and tectonism that constituted the Laramide orogeny. The stock lies between the north-south trending surface traces of thrust faults to the west and east (Figure 2). Thrust faults to the east are extrapolated to depths below the stocks and batholiths in the Marysville district. Whether the thrust faults cut the batholiths or are intruded by them is controversial.[10] The most popular interpretations extrapolate the thrust faults to a position parallel to crystalline basement[19] and show the basement and the thrust faults intersected by the plutons.[10] Normal faults post-date the thrust faults and the plutons. The normal faults form a trend parallel to the Rocky Mountain trench in northern Montana and Alberta (Figure 2). Numerous north striking normal faults are mapped within 50 km of the Marysville stock.[19]

The Empire Creek stock, which is associated with the heat flow anomaly, is not exposed at the surface and was intruded at a later date (40Ma). It is located adjacent to the Marysville stock on the southwest side.

2. Local Geology

2.1 Metasedimentary Rocks

The Marysville and Empire Creek stocks intruded and metamorphosed precambrian shales, limestones and dolomites. The most recent geologic map (Figure 4) by Blackwell et al[20] enhances the regional maps of Barrell[12], Knopf[13] and Bierwagen.[21] The Empire Creek Stock, which is associated with the heat flow

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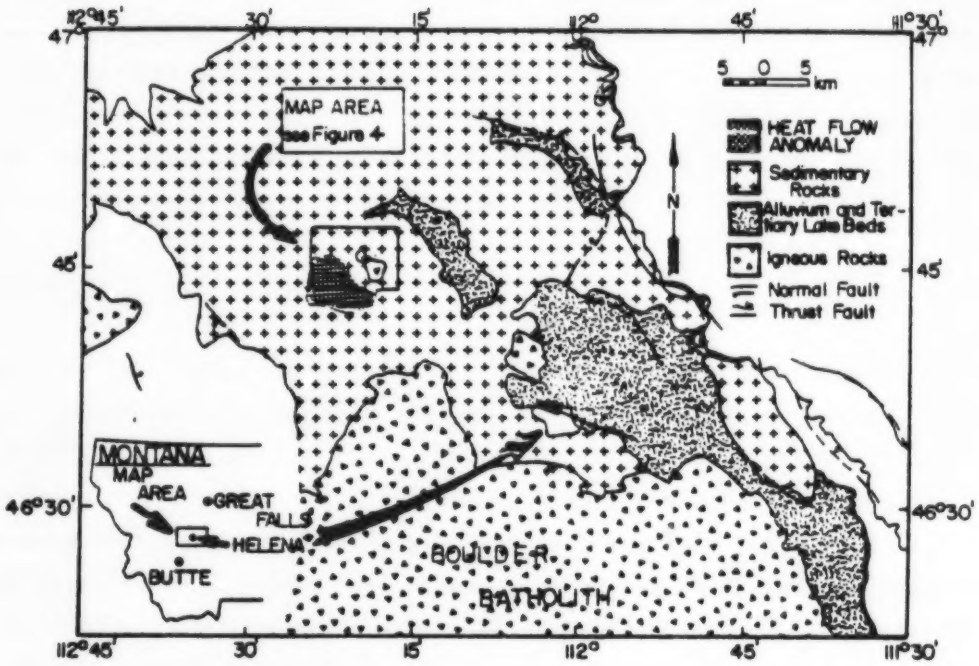

FIGURE 3-GENERALIZED GEOLOGIC MAP OF THE HELENA, MONTANA REGION AFTER FRIEDLINE ET AL[11].

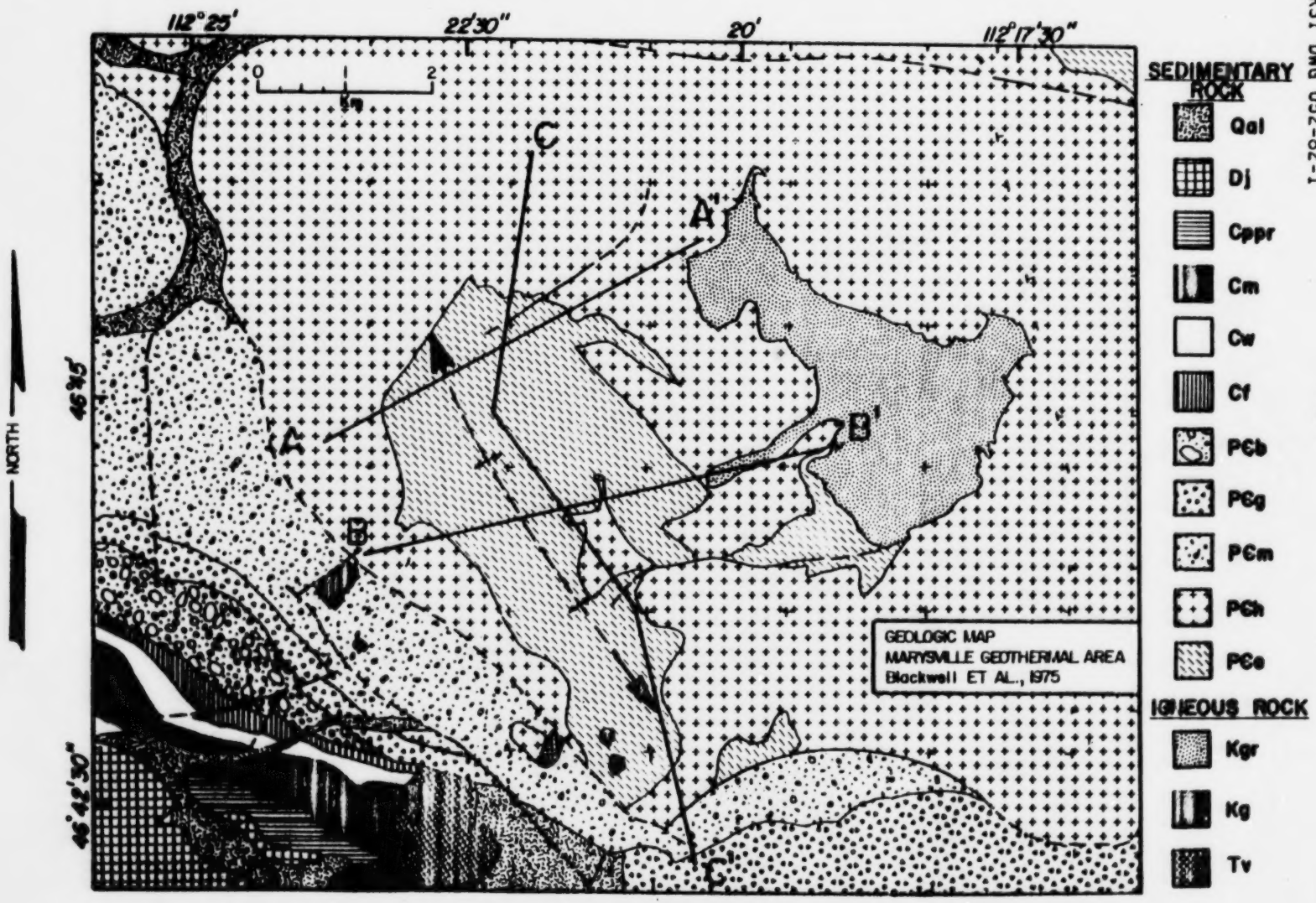

FIGURE 4- GEOLOGIC MAP OF THE MARYSVILLE GEOTHERMAL AREA. CROSS SECTIONS FOR PROFILES AA' AND BB' ARE SHOWN IN FIGURE 5 (FROM BLACKWELL ET AL.[20])

anomaly, is not exposed at the surface, but is located below the surface expression of the Empire Shale, which forms a broad dome over the stock (Figure 4). Rice[22] provided details on the progressive metamorphism of limestones in the Marysville area and in the metamorphic aureole near the Boulder batholith.[23] Two formations, the Helena Limestone and the Empire Shale, occupy most of the area of the geologic map (Figure 4). Both formations are part of the Precambrian Belt Series. According to Blackwell et al[20], the Empire Shale is a biotite-rich siliceous to calcareous shale which forms a large dome to the southwest of the Marysville stock. The Helena Limestone is a siliceous limestone and dolomite with interbeds of quartzite and shale. Other formations exposed in the area are the Spokane Shale below the Empire Shale and the Marsh Shale, the Greenhorn and the Black Mountain Quartzites above the Helena. Lower Paleozoic to Cretaceous units unconformably overlie the Belt rocks in a major syncline southwest of the geothermal area.

2.2 Igneous Activity

A summary of the igneous activity in the area is presented in Table 1. The intrusion of the Marysville stock, 79 Ma[24] was the first major event recorded in these rocks after the intrusion of microdiorite sills during the Precambrian. Four igneous intrusive events apparently occurred in the Tertiary. Blackwell et al[20] reported dates suggesting that the Bald Butte plug intruded about 49 Ma (Eocene), and numerous dikes and sills were intruded about 48 Ma (Eocene) with accompanying extrusive igneous activity. (The dates of the dikes and sills southwest of Marysville are uncertain. Blackwell et al[20] dated the sills at 37-40 Ma, Blackwell et al[25] dated them at 48 Ma.) The Empire Creek stock (40 Ma, Oligocene) is not exposed. It is a quartz-porphyry stock southwest of the Marysville stock in the Empire formation. Outcrops of Oligocene rhyolite flows are widely scattered suggesting that erosion has removed a very extensive volcanic field. The most recent event listed in Table 1 is the hypothesized intrusion that caused the geothermal anomaly. The depth is unknown and the dates are inferred from conductive heat transfer models.[26]

Table 1: Major Igneous Events in the Marysville, Montana Area

Event	Age
Intrusive Causing the Geothermal Anomaly	Quaternary or Recent (20-50 k yr)
Rhyolite Flows	Oligocene (37 Ma)
Empire Creek Stock	Oligocene (40 Ma)
Hornblende Diorite Dikes and Sills	Eocene (48 Ma)
Bald Butte Stock	Eocene (49 Ma)
Marysville Stock	Cretaceous (79 Ma)
Microdiorite Sills	Precambrian (?)

The Empire Creek and the Bald Butte stocks were discovered when drill holes intersected them during the geothermal study by McSpaoden.[7] The Empire Creek stock is a large porphyritic granite adjacent to the southwest border of the Marysville stock. The Bald Butte stock is a small porphyry stock shaped like a needle that intrudes the Helena formation (Figure 5 cross-section CC'). The drill holes, geophysical modeling and field mapping were used to construct cross sections illustrating the spatial relations among the three stocks (Figure 5).

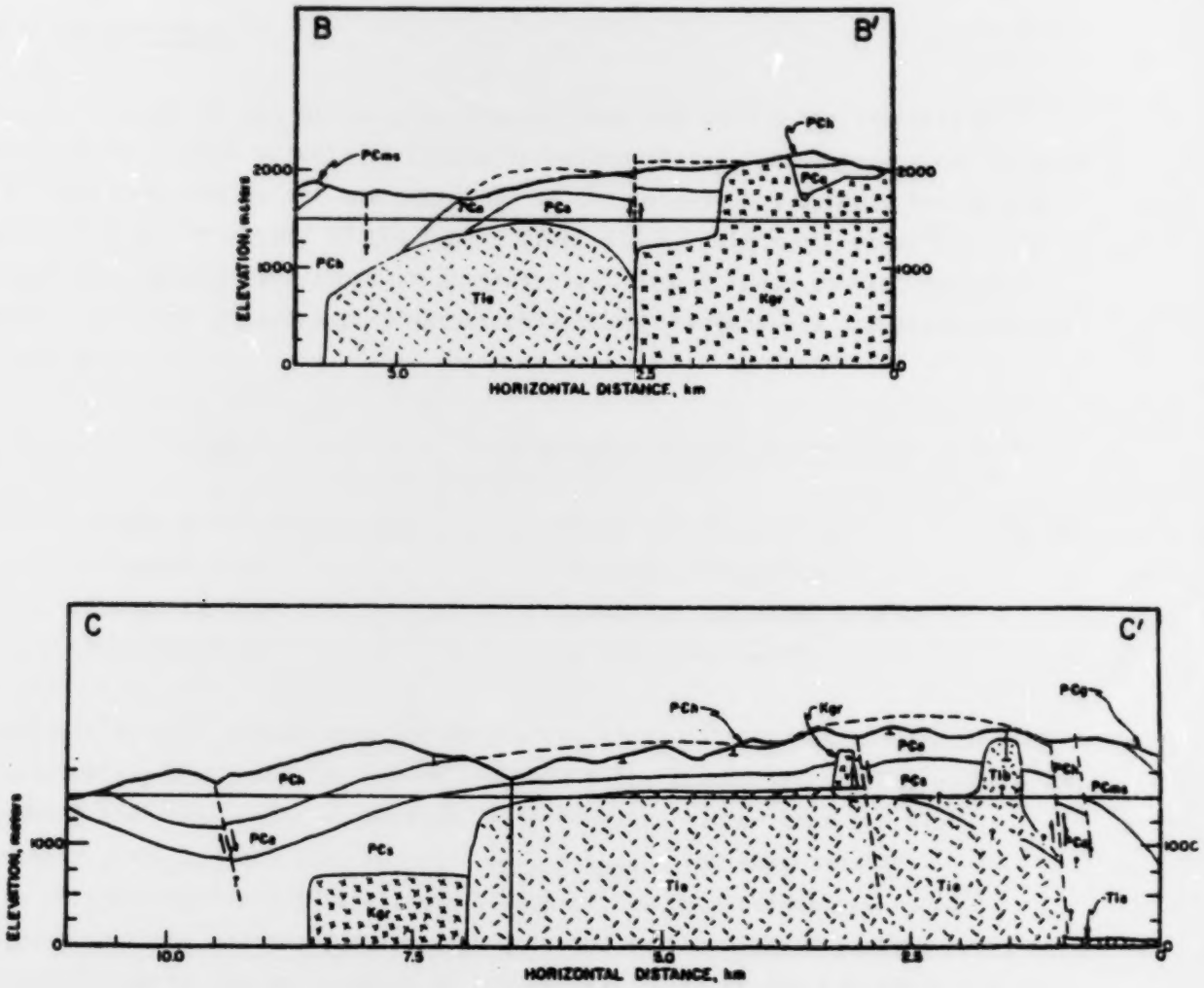

FIGURE 5- CROSS SECTIONS OF THE MARYSVILLE GEOTHERMAL AREA. LOCATIONS OF BB' AND CC' ARE SHOWN ON FIGURE 4. Kgr = MARYSVILLE STOCK, Tie = EMPIRE CREEK STOCK, Tib = BALD BUTTE STOCK. (FROM BLACKWELL ET AL[20]).

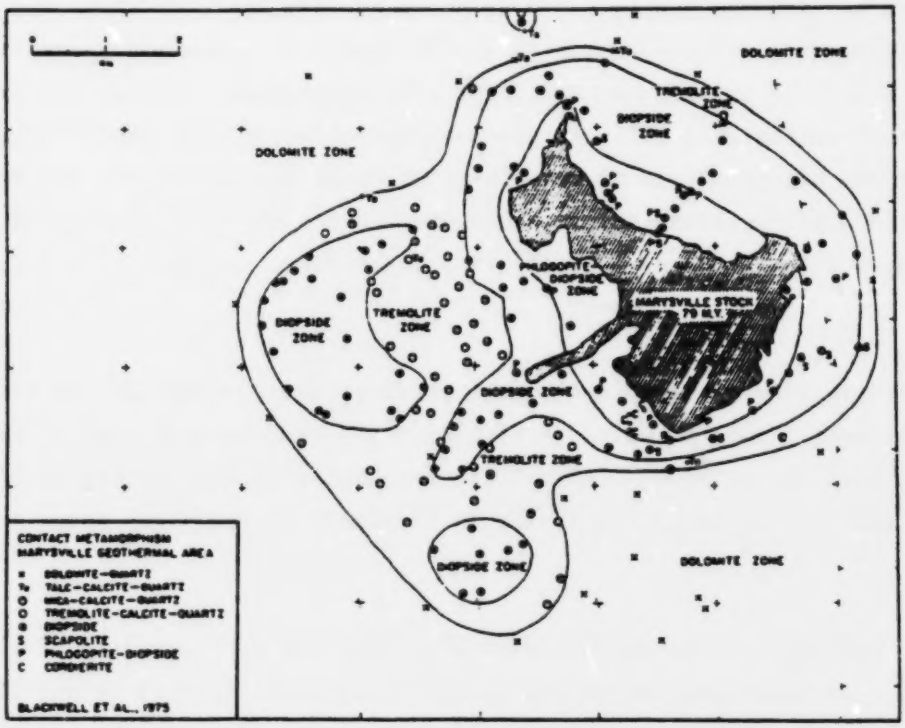

FIGURE 6-CONTACT METAMORPHISM IN THE MARYSVILLE GEOTHERMAL AREA. MAJOR METAMORPHIC ZONES ARE IDENTIFIED BY THE INDEX ASSEMBLAGE, AND ISOGRADES ARE DRAWN BETWEEN THE ZONES (FROM BLACKWELL ET AL[20]).

2.3 Metamorphism

The emplacement of the Marysville, Empire Creek and Bald Butte intrusives resulted in a broad aureole of thermally metamorphosed sedimentary rocks (Figure 6). Detailed studies of the petrology of the metamorphic aureole led to the search for and discovery of the Empire Creek stock. Blackwell et al[20] mapped four generalized zones of progressively more intense contact metamorphism. In order of decreasing metamorphic grade (temperature and pressure) the zones are:

Zone	Diagnostic Mineral Assemblage
Diopside-Phlogopite Zone	diopside, phlogopite
Diopside Zone	diopside, tremolite
Tremolite Zone	tremolite, calcite, quartz
Dolomite Zone	dolomite and quartz

Blackwell et al[20] argued that the Marysville stock intruded at a depth of approximately 2 km, and the Empire and Bald Butte stocks intruded at about 1 km, assuming the rock pressures were not significantly higher than the fluid pressures, P_{fluid}, and that $P_{fluid} = P_{CO2} + P_{H2O}$. The experimental data on the diagnostic mineral assemblages of the metasedimentary rocks[51] suggest that the maximum temperatures attained in the metasedimentary rocks were 500-600°C due to the emplacement of the Marysville stock and 400-500°C due to the emplacement of the Empire Creek and Bald Butte Stocks.

2.4. Nature of the Igneous Intrusions

The Marysville stock is granodiorite in composition[13] and was apparently emplaced at a shallow depth.[12] Blackwell et al[20] estimated the depth of emplacement at 2 km. Barrell[12] observed cross-cutting relations that implied the emplacement mode was stoping and arching of the surrounding sediments. No vein fillings in the Marysville stock are described.

A dark gray dacite porphyry, which intersects the deep borehole in the Empire Formation above the Empire Creek stock, was intruded after the intrusion of the Marysville stock but before the Empire Creek stock. The dacite porphyry was metamorphosed and fractured during the intrusion of the Empire Creek stock.[20]

The Empire Creek stock is light pink to greenish-gray granite porphyry in the uppermost portions. Downward, it grades into a more equigranular pink granite. The upper portions contain phenocrysts of plagioclase and biotite in a fine grained (sugary) ground mass of orthoclase and quartz. The plagioclase is highly altered and the orthoclase is slightly altered to kaolinite and montmorillonite and replaced by sericite. Accessory minerals include fluorite, sphene, zircon, and pyrite. Fluorite, calcite and sericite were found in veins in the upper section.

The deeper part of the Empire Creek stock is a more equigranular pink granite. The orthoclase is less altered than the plagioclase, which in some places is highly altered to kaolinite with minor montmorillonite. Fluorite was observed in most of the cores described by Blackwell et al[20] and a fluorite vein was described.

Blackwell et al[20] distinguished two sets of mineral-filled veins. One set of veins, interpreted as high-temperature veins, are filled with quartz, calcite, dolomite, adularia, fluorite, tremolite, phlogopite, green biotite, muscovite or sericite, montmorillonite, chlorite, clinozoisite, plagioclase, pyrite, limonite, hematite, sphalerite, galena and molybdenite. The high temperature veins also contain rock chips(??). The later, low-temperature veins contain dolomite, calcite and quartz. The dolomite and quartz would have reacted to form talc if they had reached temperatures greater than 300°C.

The Empire Creek stock contains open fractures, some of which are slickensided and filled with montmorillonite. Blackwell et al[20] interpreted the orientations of the slickensides and striations to indicate horizontal movement.

Other horizontal fractures are later and may have been caused by final cooling or release of stress when the core was drilled, probably the latter.

3. Borehole Lithology

The 2-km deep borehole penetrated the Empire Creek stock at 294m depth and intersected several fracture zones. A generalized lithology is presented in Figure 7. In general, the stock is a weathered granite porphyry at shallow depths and a pink porphyritic granite in deeper regions. The phenocryst sizes increase with depth, indicative of relatively rapid cooling near the periphery of the stock and slower cooling in the interior. Miarolitic cavities observed in the three cores below 1600m are also characteristic of plutons and pegmatites that cool slowly enough to trap gas pockets. The stock is altered along the entire borehole but the most highly altered regions are above 1300m. The description of the deep exploratory borehole[20] is presented in detail in Appendix A.

Some information regarding the drilling methods and casing is given in Chapter D, Section 2.

4. Synthesis

The Marysville stock was emplaced during the intense folding, thrusting and igneous activity that is generally referred to as the Laramide orogeny. The Marysville stock metamorphosed the Precambrian Belt series sedimentary rocks that are in the upper plates of most of the large overthrust faults in Montana. Forty million years later, the Empire Creek stock, the dacite porphyry, the Bald Butte stock and possibly several other undiscovered stocks intruded the Marysville rocks increasing the volume of metamorphosed sediments. Finally, a new heat source was introduced below the Empire Creek and Marysville stocks at least two kilometers below the present erosional surface. It seems highly unlikely that the heat flow anomaly is associated with residual heat of emplacement of the Empire Creek stock since plutons generally cool within one

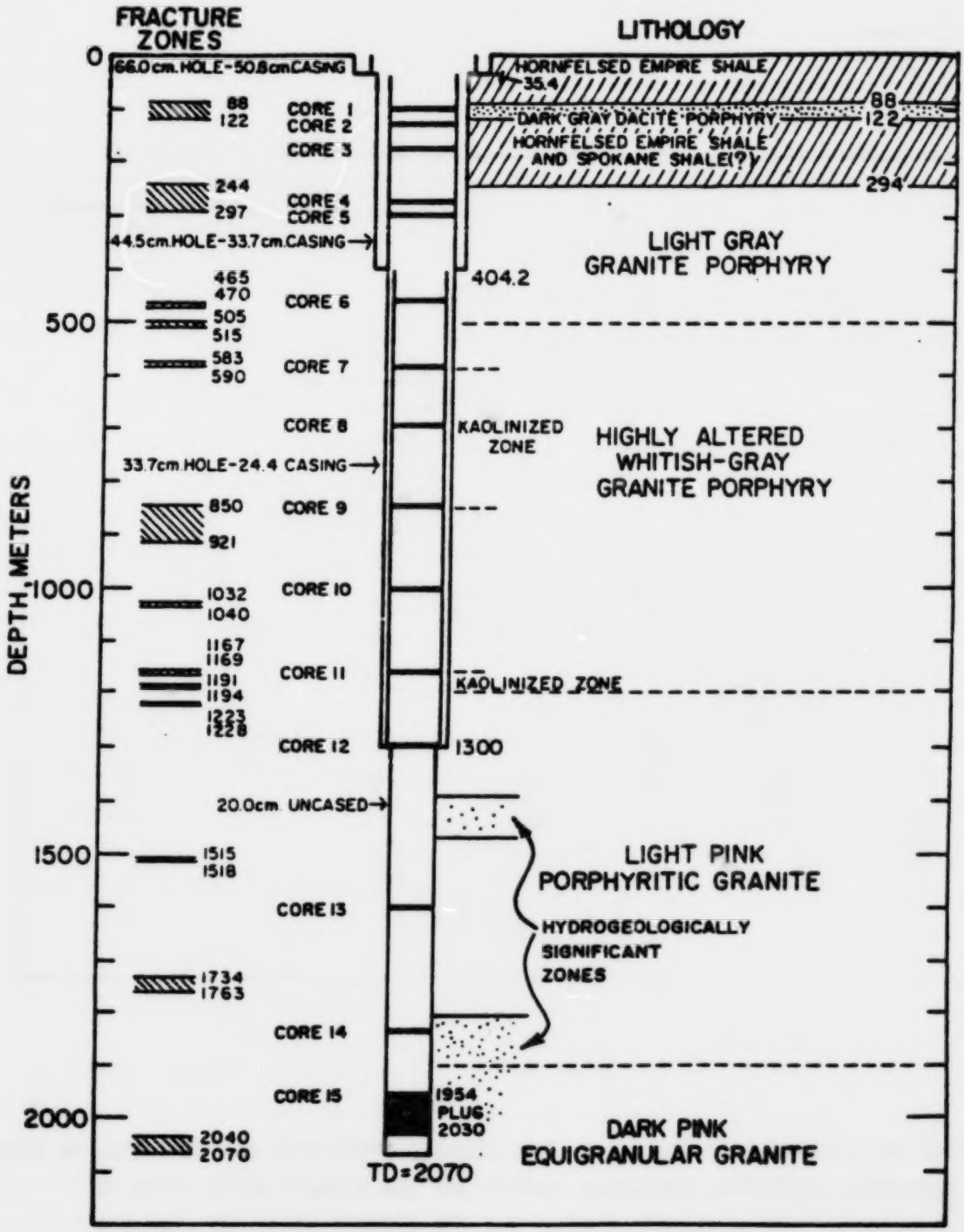

FIGURE 7-LITHOLOGY, LOCATION OF FRACTURE ZONES DETERMINED BY DRILLING, HOLE CASING SIZE, AND CORE LOCATIONS VERSUS DEPTH IN THE DEEP BOREHOLE (AFTER BLACKWELL ET AL[20]).

million years of emplacement.[53] Calculations based on conductive heat transfer suggest the heat flow anomaly was introduced a few tens of thousands of years ago.[27]

The geological setting of the Empire Creek stock and the Marysville region has been described in detail because it has an important bearing on the cause and genesis of the heat flow anomaly. It is also important to realize that in spite of the similarities between the geology of the heat flow anomaly and the geological setting which is proposed for a repository in the Canadian Shield, there are also fundamental differences. These differences include the ages of the igneous intrusives. In addition, the shield granites are the eroded roots of orogenic belts, and often crystallized under higher pressures and temperatures than the Laramide plutons.

C. GEOPHYSICS

A comprehensive suite of geophysical exploration surveys was used in the exploration of the geothermal area since one of the objectives was to learn what tools would be best suited for studying blind geothermal areas.[5,6,7] The various geophysical methods and their degree of success are described below.

1. Surface Exploration

1.1 Heat Flow

Heat flow investigations comprising temperature and thermal conductivity determinations in approximately 30 boreholes[4,6,7,27] led to the original discovery of the heat flow anomaly and delineated its areal extent. The resulting heat flow and temperature gradient contours are shown in Figure 8 where it is seen that the anomaly coincides with the Empire Creek and Bald Butte stocks. A maximum heat flow of 800 mW/m^2 and geothermal gradient of about 240°C/km are reached. A sharp heat flow contrast exists between the Empire Creek and Marysville stocks, and the reason for this is not clear.

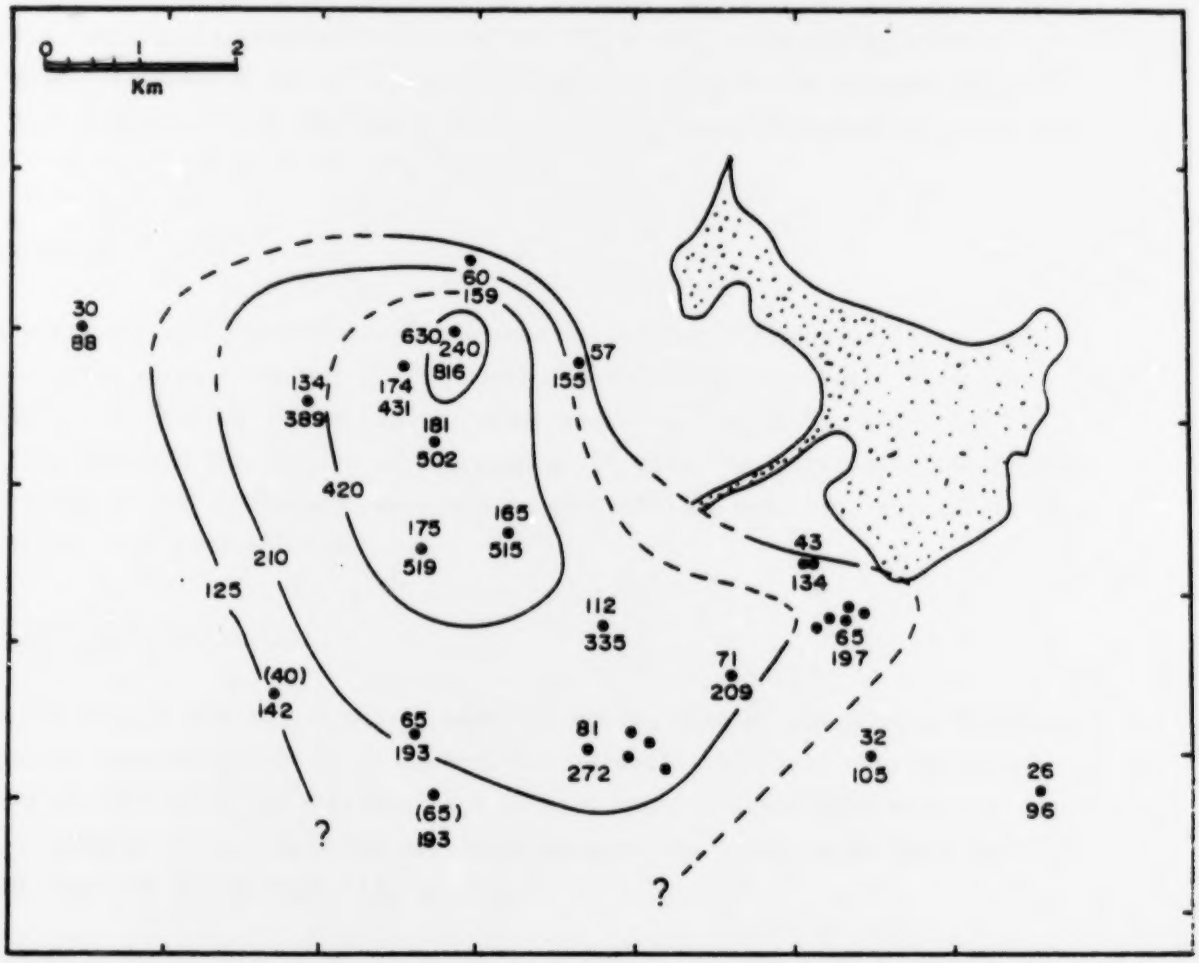

FIGURE 8- HEAT FLOW AND GEOTHERMAL GRADIENT MAP. LOCATIONS OF BOREHOLES ARE SHOWN BY DOTS; UPPER FIGURES ARE THE TERRAIN CORRECTED GEOTHERMAL GRADIENTS (°C/Km), THE LOWER FIGURES ARE THE TERRAIN CORRECTED HEAT FLOWS(mW/m^2). (FROM BLACKWELL ET AT [20]). THE STIPLED AREA SHOWS THE OUTCROP OF THE MARYSVILLE STOCK. HEAT FLOW IS ALSO INDICATED BY CONTOURS.

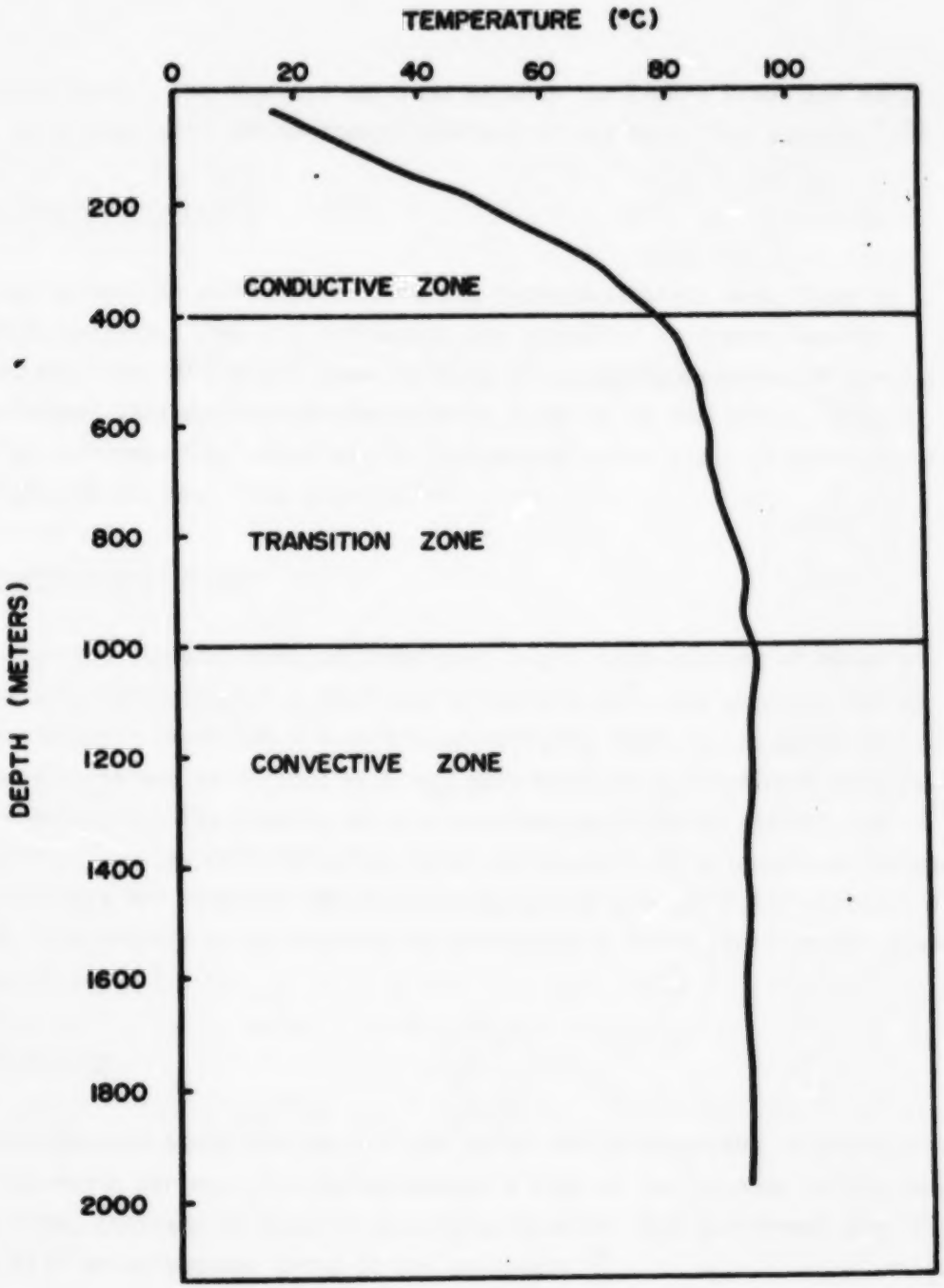

FIGURE 9- Temperatures Measured in the Deep Borehole (74-11-16) as a Function of Depth [20].

The temperature profile measured in the deep borehole (74-11-16) is shown in Figure 9.[20] A steep, linear temperature gradient is observed from 0 to 400 m depth and is associated with conductive heat transfer. A zero to slightly negative temperature gradient occurs below 1000 m and is associated with a groundwater convection cell. A thermal transition zone exists between 400 and 1000 m. It appears that the Empire Shale is acting as an impermeable cap on the convective flow system in the granite stock.

1.2 Gravity

The gravity survey revealed a negative anomaly which has good correlation with the heat flow anomaly, except to the south. A model based on the gravity data has similar dimensions to the Empire Creek stock[20] and, together with the heat flow data and the results of the deep drill hole, indicates that the Empire Creek stock is the geothermal reservoir in which fluids are circulating, giving rise to the heat flow anomaly.

1.3 Electrical Resistivity

The United States Geological Survey used the roving dipole technique with source to receiver separations of up to several kilometers. They felt they had penetrations to 600-1000m and obtained high to very high resistivities over the geothermal anomaly. No correlation was found between the interpreted resistivities and the location of the heat flow anomaly.[6]

1.4 Magnetotellurics

Eighty-one audio magnetotelluric (AMT) soundings were carried out in the frequency range of 20 to 10^4Hz. In addition, 12 magnetotelluric (MT) stations (0.1 to 0.001 Hz) were occupied. High resistivities were found (1000 to 3000 ohm-m) with no correlation in trends with the heat flow anomaly.[20]

1.5 Magnetics

About 800 stations recorded the total magnetic field. No anomaly was detected over the geothermal area; an anomaly of about 1600 gammas was found over the

Marysville stock. The magnetic contrast between the Empire Creek and Marysville stocks correlates with the northeast boundary of the heat flow anomaly.[6,20]

1.6 Airborne Infra-red

Infra-red surveys in two bands of 3-5u and 8-15u wavelength were flown at 10,000 feet above terrain. They did not detect any anomalies in ground surface temperature. They did detect some increase in canopy temperature of trees in the geothermal area due to warm water being drawn up by the roots. Ground follow-up confirmed that there was an increase of about 1.5°C in tree canopies in the area of the heat flow anomaly.[5,7]

1.7 Seismic Ground Noise

Forty recording stations were deployed over a grid with spacing of about 1.5 km. Each station, consisting of a short period seismometer, was occupied for 12 hours or longer. There was a negative correlation, that is, an occurrence of low ground noise was associated with the geothermal area, in direct contrast to what was expected. The results were interpreted as evidence against the presence of a shallow convecting hot water reservoir. An alternative interpretation was that the observations could be caused by the recording stations over the heat flow anomaly being situated on particularly solid rock, rather than any deep-seated cause.[6]

1.8 Seismicity

A micro-earthquake study was carried out using six seismographs in three arrays over a two-month period. The survey showed a lack of earthquakes in the geothermal area, contrary to what is expected. However, the geothermal area is on-line with an earthquake trend to the southeast.[28]

2. Borehole Logging

The drilling of the deep borehole (2.1 km) allowed many of the hypotheses and interpretations from the geophysical and geological surveys to be tested. Two

Schlumberger logs were run; from 0 to 404m before casing, and from 404m to bottom before casing. Cement bond logs were run after each casing. The following tests were conducted:

(1) Borehole caliper log and sonic log with gamma ray (measures hole diameter, acoustic velocity, and natural radioactivity in the rock).

(2) Dual induction laterolog (determines the formation resistivity by eddy current induction and flow of a focused direct current).

(3) Formation density gamma ray log (determines the formation density, hole diameter and natural radioactivity).

(4) Compensated neutron log (measures the formation porosity and hydrogen concentrations by means of neutron source).

(5) Electrical survey (measures resistivity of the formation).

(6) Four-arm Digital Dipmeter (measures the dip angle and dip direction of fractures and bedding planes by correlating changes of formation electrical resistivity).

In addition, many temperature logs and some hydrogeological tests were run during and after drilling of the borehole.[7] The latter are described in Chapter D. The borehole geophysical logs were combined with drilling records, core logs and cuttings logs to produce lithological logs and logs of fracture zones. These are illustrated in Figure 7.

The most important piece of information arising from the borehole was that massive groundwater flow and convection was occurring through fractures in the Empire Creek stock.[7] This result had not been expected on the basis of the geophysical surveys.

3. Discussion

The geothermal evaluation of the Marysville region is an instructive case history since the geological and geophysical surveys were very comprehensive in scope. In addition, the deep borehole allowed actual subsurface conditions to be correlated to the predictions made by the geo-surveys.

High groundwater flow rates observed in fractures in the borehole suggest that the over-all permeability is high. However, this phenomenon had not been predicted by the geophysical surveys. In particular, electrical methods such as resistivity and magnetotellurics were not useful in assessing the hydrogeological conditions. This is probably caused by the low porosity of the rock mass. As will be discussed later (Chapter E), hydrothermal flow may be enhancing the permeability of the existing fracture network. Thus, a heat source in a jointed crystalline rock appears to be capable of causing relatively high flow rates and enhanced permeability while maintaining relatively low overall porosity. This fact is consistent with current concepts regarding flow in fractured media, and has important implications for predictions regarding groundwater flow and radionuclide transport in the vicinity of a nuclear waste repository.

The most useful tools in delineating the geothermal area were the heat flow measurements, and the gravity and magnetic surveys. In particular, the importance of direct subsurface observation via boreholes cannot be overemphasized. As mentioned previously, resistivity and magnetotelluric methods were not useful. This is further illustrated by comparing average apparent resistivity versus frequency plots for the Marysville geothermal region to curves obtained in the Canadian Shield (Figure 10).[29] It is seen that the curves are essentially the same, although the groundwater and thermal regimes for the Shield are dramatically different from the Marysville area.

There is a pronounced lack of earthquakes in the geothermal region. It may be that the hydrothermal activity is causing glide/creep along the existing faults and not allowing stick-slip behaviour. Should this conjecture be correct, it raises the intriguing question of whether a nuclear waste repository would lead to a lower probability of earthquakes in its immediate vicinity.

The geophysical surveys which AECL has been conducting at its research areas[30,31,32,33] are summarized in Table 2. It is seen that the investigations performed by AECL are even more comprehensive than the broad suite of studies performed at Marysville. It certainly does not appear that any tools have been overlooked; however, the Marysville studies suggest that less emphasis should be placed on electrical methods.

There is an intriguing contrast between the Marysville and Empire Creek stocks regarding their heat flow, gravity and magnetic characteristics, although their electrical resistivity and seismicity signatures appear the same. Does the Empire Creek stock act as a conduit for hydrothermal convection driven by a deep heat source? Why is the neighbouring Marysville stock different? Is the heat flow difference caused by the location of the deep heat source or by structural differences in the two stocks? The next two sections will attempt to answer these important questions.

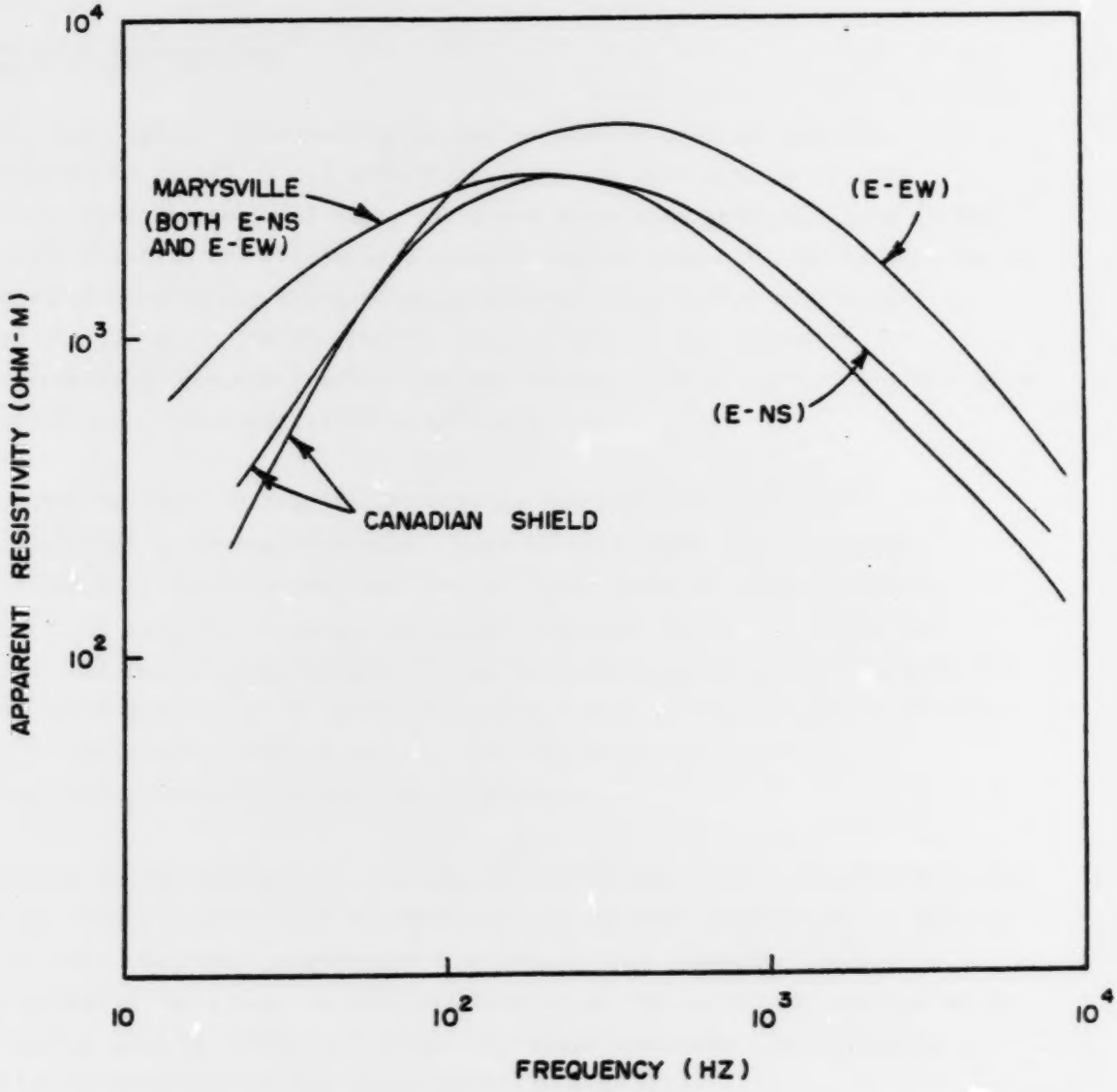

FIGURE 10- COMPARISON OF APPARENT RESISTIVITY VERSUS FREQUENCY CUREVS FROM MARYSVILLE[20] AND FROM THE CANADIAN SHIELD[29]. LABELS REFER TO THE ORIENTATION OF THE ELECTRIC MEASUREMENTS.

Table 2: Summary of Geophysical Surveys Used by AECL

Airborne	Electromagnetic (EM)
	Very low frequency (VLF) EM
	Total magnetic field
	Aeromagnetic gradiometer
Surface	Seismic reflection
	Seismic refraction
	Magnetotelluric (tensor)*
	Audio magnetotelluric*
	Magnetometric
	Resistivity*/induced polarization
	VLF-EM
	Transient EM
	Gravity*
	Magnetic*
	Radar
Borehole	Television
	Tubewave seismic
	Temperature logging*
	Natural gamma*
	Neutron-gamma*
	Gamma-gamma*
	Caliper*
	Self-potential
	Resistivity*
	Sonic velocity*
	Fluid conductivity
	VLF-EM
	Radar

*Indicates surveys which were also performed at Marysville.

D. HYDROGEOLOGY

1. Physical Hydrogeology

Although the regional hydrogeology of the Marysville area has not been investigated in detail, a conceptualization can be developed by drawing inferences from the regional topographic and hydrologic setting. Some of the inferences drawn in the following discussion may be somewhat speculative, due to the relative uncertainty surrounding groundwater flow system development in crystalline terrain. The uncertainty lies largely in the degree of interconnectivity between fracture systems in this type of terrain and the scale over which any interconnectivity is effective.

Groundwater movement is significant only in the fractures and other discontinuities in crystalline rock. Even in relatively well fractured crystalline rocks, single features such as shear zones or large fractures represent the most significant groundwater transport zones. Although the discrete features are significant, it has recently been shown that permeability tensors for fractured media can be developed from a sufficient number of field tests.[34] The significance of this is that the fractured media can be assessed using equivalent porous media concepts.

Groundwater movement occurs in response to gravity and pressure potentials, and these are strongly influenced by the local and regional topography, as well as heat sources. Regional groundwater flow occurs from topographically high to topographically low areas, usually discharging at the surface as springs or to water bodies such as rivers and lakes. In these instances, the hydraulic potential is developed in the topographically high areas.

The Marysville area is situated in the Northern Rocky Mountain physiographic province and Montane (rugged, steep mountains with narrow intermountain basins) physiographic region. The mountain slopes are highly variable approaching a maximum of approximately 50 percent slope. Relief is approximately 600 metres, with a maximum elevation of 2234 m at Mt. Belmont and a minimum elevation of

about 1616m in the Empire River bottoms. Relief of this magnitude suggests that relatively steep groundwater hydraulic gradients may also exist.

The nearest stream gauges on perennial streams indicate a minimum recorded flow of about 0.06 m^3/S (60 l/s). The mean annual precipitation at Marysville is 49 cm and the mean annual temperature is 4.8°C. However, with the variability in elevation and exposure, extreme contrasts in precipitation and temperature can be found. Most of the precipitation occurs as snowfall from winter storms. The water equivalent of the average annual snowfall in the Marysville area approaches 46 to 50 cm. The principal source of groundwater recharge is spring snowmelt and groundwater recharge likely occurs over a relatively short period in the spring.

Surface water drainage in the area has developed in a dendritic drainage pattern with Empire Creek representing the principal surface drainage from the geothermal area. Empire Creek is a tributary of Lost Horse Creek, which is, in turn, a tributary of Little Prickly Pear Creek in the Upper Missouri River basin. All of these creeks are characterized as perennial, suggesting that a baseflow is derived from groundwater discharge.

The water table in the area is generally within 1 to 3 metres below ground surface [35] and corresponds roughly to the topography. Groundwater recharge occurs beneath the topographically high areas and groundwater discharge is manifest in the perennial nature of the streams in such a relatively arid climate.

Hot springs are the usual surface manifestation of geothermal areas; however, the nearest known hot spring to the Empire Creek stock is about 17 km distant. All local surface drainage east of the Continental Divide (about 20 km to the west) has been sampled and no sign of hot spring activity has been noted.

2. Borehole Hydrogeologic Data

The geothermal exploratory borehole was sited on the Empire Creek stock and advanced using air as the circulation medium.[7] The first significant water encountered during drilling occurred at around 460 metres, whereas the first

large flows were encountered at approximately 550 meters. At the 550 meter depth, the hole appeared capable of producing about 375 litres per minute (unknown drawdown). At this point, the drilling method was changed to a mixture of air and water, so as to maintain sufficient head in the hole and eliminate "pumping" the groundwater system. A 12 3/8 inch casing was set from 35 metres to 404 metres and cemented in place after temperature and other geophysical logs were run. Between 404 metres and 1300 metres, a 9 5/8 inch casing was set; however, the cement job was unsuccessful and only the bottom few metres are encased in cement. Groundwater circulation outside the 9 5/8 inch casing is therefore quite likely. Between 1300 metres and the total depth of 2070 metres, a 7 7/8 inch hole was completed and left uncased. The lowest portion of the hole was acting as a significant drain on the borehole and was subsequently sealed with a 115 metre cement plug in the bottom of the hole.[7,36]

There were a few drill stem tests conducted during the drilling phase of the program; however, the results of these are not available for interpretation. They were apparently conducted primarily for the purpose of establishing flow rates and collecting water samples, and the in-situ pressures were not measured. However, the information can provide a basis for preliminary hydrogeologic interpretation.

Intraborehole water flow measurements were conducted with full bore spinner logs, packer flowmeter measurements and the Birdwell ^{131}I isotope log. Before the casings were installed, there was a downflow of about 16 litres/sec from the 1000 m zone to the major fracture zone located between 2040 and 2070 m depth. After the casings were installed and the lower portion plugged with cement, the flow was reduced to less than one litre/sec. Subsequent flow measurements in the uncased portion (1300 m to 1954 m) of the borehole showed the flow changed from downflow to upflow over a period of approximately 15 months (up to 1977).[36] The slow reversal suggests that the system was not previously and still (by 1977) may not have been in a stable condition with respect to the presence of the borehole.

The zones around 1400 metres and 1800 to 1900 metres depth are quite significant to the re-equilibration of the system. In both the upflow and downflow conditions, flow either originated or terminated in these zones; i.e., they

represented groundwater sources or sinks in the borehole (Figure 7). Although the 1400 metre zone is not identified as a major fracture zone on most of the project diagrams, McSpadden[36] suggested that the geophysical logging results show the zone to be highly fractured. He did not indicate, however, on which logs this interpretation is based. The temperature logs do not show any anomalies in this particular zone. These two zones (1400 m and 1800 to 1900 m), although significant under the present conditions, are less significant and likely much less permeable than the zones cased off at around 1000 metres and cement plugged at around 2050 metres. The presence of these more permeable zones, which required sealing, suggests that a relatively active groundwater flow system is present in the Empire Creek stock area.

Temperatures in the borehole had still not equilibrated by 1977, which led to speculation by McSpadden[36] that the well has caused a significant change in the local convective patterns and that the thermal transients are due to the presence of the borehole in the convection system. This is probably correct since the borehole, as a vertical conduit, must represent the single most significant perturbation on the groundwater circulation system.

The two most significant aspects of the hydrogeological data obtained from the borehole are:

(1) The relatively stable water level at about 166 metres below ground surface and

(2) The thermal profile indicating heat transport by conduction (i.e. noncirculating water) in the upper 600 metres and an isothermal zone likely controlled by groundwater convection from 600 metres to the total depth of the borehole.

The water level at 166 metres below ground surface is a composite water level representing the combined effects of hydraulic head and permeability of the uncased hole from 1300 to 1954 metres. This relatively low water level suggests that there may be a "drain" acting on the groundwater system which has lowered the hydraulic head at depth. Without sufficient permeability and larger scale flow system data, it is not possible to calculate the possible head dissipation;

however, a head as low as 166 metres, without noticeable variation over the seasons, is considered to be suggestive of a possible surface discharge situation. The water table in the immediate borehole vicinity is very near ground surface, as evidenced by near-site observations and measurements in a mineral exploration hole ("slant hole"[36]). The slant hole (unknown depth) is located about 180 metres east of the test well and maintains an artesian flow of approximately 2 litres/min. In addition, flow in a small stream which enters Empire Creek just west of the drill site is maintained by surface springs (elevation 1768 metres) located 400 metres to the southeast of the drillsite. Both these observations support the presence of a shallow water table and the implication of the possible surface connection to depth mentioned above.

The thermal profile, which indicates a thermal conduction regime in the upper 600 metres of rock and a convection, or relatively isothermal, regime below that, also provides significant basis on which to draw conclusions regarding the overall hydrogeologic regime. The drilling, coring and geophysical logging showed significant indications of major subhorizontal structural features such as individual fractures and fracture or shear zones. The likely extent and high permeability of these features is evidenced by the substantial amount of water (16 litres/sec) the lower-most zone (2050 m) was capable of accepting, under a very slight hydraulic gradient (about 20 kPa differential calculated between the 1000 m and 2050 m zones[36]). The fact that the 600 m to 2070 m depth shows relatively isothermal conditions strongly suggests that there is a vertical fracture system which provides for good hydraulic connectivity between major subhorizontal permeable zones. The net result of such connectivity is to allow convection cells to develop which have subsequently heated a large portion of the rock mass.

3. Hydrogeochemistry

The general chemical characteristics of shallow groundwater in the area were discussed by Wilke and Coffin[37] and Wilke.[35] The shallow ground water is predominantly a calcium bicarbonate water with a median chloride concentration of about 8 mg/L (range 1.4 to 120 mg/L). The general chemical characteristics of thermal spring waters in Montana are discussed by Mariner

et al.[38] The thermal springs are usually dilute to slightly saline sodium-bicarbonate type water, with neutral to slightly alkaline pH's. The waters are theoretically in thermodynamic equilibrium with calcite and fluorite and chalcedony is considered to control silica concentrations. Geochemical calculations based on silica concentrations and Na-K-Ca ratios indicate the springs likely originate from low temperature (<100°C) aquifers. Nitrogen is generally the principal dissolved gas and the ^{2}H content is typical of western Montana meteoric water.[7]

Water samples were collected[36] from the slant hole artesian flow, Spring Creek 400 m southeast of the drill site, and from several depths in the Marysville borehole using pressurized water sampling techniques. The results of the chemical analyses are presented in Table 3.

It is clear from the results shown in Table 3 that the samples from the near surface (<171 m) in the geothermal well and from the slant hole and Spring Creek are all similar in composition, showing typical shallow groundwater calcium-bicarbonate composition and low chloride, sulfur and fluoride concentrations. These analyses are representative of shallow groundwater in the area.

The deeper samples from the geothermal well are quite similar generally demonstrating a dilute sodium-bicarbonate-sulfate water. The chloride content is relatively low and the most obvious feature of the water relating it to other thermal springs in the area is the relatively high fluoride content. There is ubiquitous fluorite in the metamorphic aureole of the Empire Creek stock and in the rock itself[20] which is undoubtedly the source of the fluoride. The overall water chemistry of the lower samples from the Marysville geothermal well are very similar to the general range of thermal spring water chemistry discussed by Mariner et al.[38] Charge balances in the analyses of Table 3 are not sufficient (with most being much less accurate than $\pm$10 percent) to proceed with geochemical model calculations for complete geochemistry. However, the chemical data are sufficient to apply the silica and Na-K-Ca geothermometry calculations.[20]

The distinct change in chemistry between the shallow samples and the deeper ones suggests that the shallow groundwater system is not in hydraulic connection with the deep groundwater circulation system in the vicinity of Spring Creek. Mixing between the shallow and deep systems may occur elsewhere.

Four deep samples from the deep geothermal well (579 m, 1035 m, 1219 m and 1750 m) were analyzed for ^{18}O content. The ^{18}O content of water of meteoric origin often "shifts" during flow through geothermal systems, if the temperature is 150°C or higher. The "shift" to an increased ^{18}O content in the water is due to exchange with the rock, increasing the ^{18}O content of the water and decreasing that of the rock. Since there is generlly very little exchangeable hydrogen in these typed of rocks, the ^{2}H was not measured.

The ^{18}O results[36] indicated little or no shift from the meteoric water line relating ^{18}O and ^{2}H in western Montana.[20] This suggests 1) that the temperatures of the geothermal source are below 150°C, and 2) the circulating water in the Empire Creek stock is of relatively recent meteoric origin. Older circulating water would be characterized by ^{18}O contents typical of glacial times, i.e. somewhat enriched in the heavy isotope.

In general, the results of the chemical analyses indicate that the relatively dilute geothermal fluid is uniform in nature, representing a sodium-bicarbonate-sulfate type water. Calculated temperatures of the heat source[20] based on the SiO_2 geothermometer are between 110 and 130°C, while those based on the Na-K-Ca geothermometer are between 165 and 180°C. The waters show little if any ^{18}O shift, and the conclusion can be drawn that the circulating thermal water is of relatively recent meteoric origin.

TABLE 3: CHEMICAL ANALYSES OF GROUNDWATER SAMPLES [36]

Sample* depth (m)	pH (field)	Ca	Mg	Na	K	Li	Zn	Cl	F	SO_2	HCO_3	NH_4	CO_2	Ar	O_2	N_2
		mg/L											%			
SH	7.4	41	6	16	2	.01	.05	5	3.5	6	103	<3				
SC	7.7	52	8	6	2	.01	<.01	4	.8	15	115	<3				
171	9.0	40	0.7	12	4	.05	7.0	8	1.3	31	74	<3				
1305	7.8	10	0.2	240	10	1.7	1.0	43	16	48	165	8				
1380	7.7	9	0.2	240	10	2.0	2.0	40	18	180	160	5				
1425	7.5	8	0.2	230	10	3.0	0.6	45	18	41	172	6				
1515	7.7	7	0.2	230	13	1.6	0.4	45	17	190	160	4	1.04	1.15	19.7	78
1608	7.8	9	0.2	230	10	2.4	1.0	43	19	200	164	6				
1753	7.9	8	0.3	240	11	2.0	2.0	48	22	210	168	9	0.46	0.97	19.4	79.2
1829	8.0		0.2	240	13	1.8	0.4	60	18	81	152	6				
1935	9.3		0.06	230	11	1.4	0.4	43	17	200	127	6				

Fe: < .005 all samples
Cu: < .01 all samples except 3(.02 mg/L)
Al: < .03 all samples
Ba: <0.2 all samples except 3(1.2mg/L)

Rb: < .05 all samples
Cs: <5.0 all samples
Hg: <1.0 all samples
Pb: <0.5 all samples

*All samples from deep borehole except SH (slant hole) and SC (Spring Creek).

4. Discussion

The relevance of the hydrogeologic conditions in the Empire Creek stock to nuclear waste disposal is readily seen from the conclusions regarding high permeability, well interconnected, subhorizontal features, circulating meteoric water and the potential for surface discharge. The available data suggest that the groundwater is capable of moving relatively rapidly through the fracture system in the crystalline rock. Transit times for water and for dissolved radionuclides can be estimated by employing some simplified concepts.

Groundwater velocities through a large well-interconnected fracture system can be calculated by assuming a large representative elementary volume and employing equivalent porous media concepts. Alternatively, if water movement is through a single fracture, the groundwater velocity can be calculated using a parallel plate model.

Most studies of groundwater flow within fractured media emphasize the dominating influence of fractures on the effective permeability of the rock mass (for example, Snow[39] and Maini and Hocking[40]). Although fractures are the principal paths of groundwater flow and solute transport, the matrix adjacent to the fractures also plays an important part in the overall solute transport process.[41] Radionuclides present in water moving through a fracture system will tend to diffuse from the fracture into the adjacent matrix. The effect of matrix diffusion is to provide solute "storage", with the rate of change of storage within the matrix related to Fick's second law of diffusion.

Transit times for radionuclides to travel from a repository to the environment may be estimated from a knowledge of the distance to be travelled and by calculating the groundwater velocity and incorporating the effects of matrix diffusion. An example of such a sensitivity analysis in fractured crystalline rock has been presented by Grisak and Pickens.[42] Given a representative velocity of 100m/year over a four km travel distance in a single planar fracture in crystalline rock, it was shown that matrix diffusion would likely reduce the

average radionuclide velocity to one percent or less of the water velocity. First exit at 4 km would occur at approximately 1000 years.

In the Marysville context, there appears to be the likelihood of permeable, subhorizontal features (fractures or fracture zones) providing a transport pathway to surface for heated water from the Empire Creek stock. The pathway is likely to be one or more of the major subhorizontal features which may or may not be interconnected by vertical fractures. It has been previously stated that the nearest known thermal spring is approximately 17 km distant. Under the mountainous terrain conditions, and assuming the groundwater table is a subdued reflection of the topography, a hydraulic gradient of 0.01 or more is quite possible. With a single fracture of 100 μm aperture and an uncertainty of approximately two orders of magnitude, groundwater velocities calculated using the parallel plate model are in the 1 to 100 m/year range. Without matrix diffusion, the travel times from source to exit point are 17,000, 1700 and 170 years, while with matrix diffusion, these may be delayed by several orders of magnitude.

The calculations are provided simply to establish a waste-emplacement framework for evaluating the significance of the highly permeable and apparently extensive features encountered during the drilling of the Empire Creek stock. It is apparent that the potential for rapid groundwater transport exists and that relatively short travel times from source to exit are possible using realistic assumptions.

E. GEOCHEMISTRY

1. Fractures, Veins and Alteration

The most important features in a rock mass are the fractures, since they form the only viable route for radionuclides to escape from a repository. An understanding of fractures and their genesis can be obtained by studying fracture filling and coating minerals and any alteration in and around the fractures. This section describes the fractures intersected by the deep borehole in the Empire Creek stock. A hypothesis is presented which accounts for some of the geophysical observations and also explains the enhanced hydrothermal activity observed in the Empire Creek stock.

The fracture filling minerals (i.e., veins) and alteration, as observed in 11 cores from the borehole[20] are summarized in Table 4. In general, the fractures were not studied extensively as part of the geothermal project. The problem is further compounded by the small amount of core obtained from the borehole. The available information is summarized below. The Empire Creek stock was intruded by numerous veins of high temperature minerals. Quartz and fluorite veins continue at depth to the deepest core and are presumed to have continued forming while the rock was cooling. Galena, sphalerite and molybdenite veins are found above the contact (Figure 7), with the molybdenite veins continuing several hundred meters below the contact. Late veins associated with the intrusion contain dolomite, calcite and quartz. The temperature of these veins was probably below 300°C. These veins might also be associated with some later event. Finally, open fractures and those containing montmorillonite may represent events late in the cooling process of the intrusion. Some of these fractures and vein fillings show slickensides and striations indicating horizontal movement. Other horizontal fractures with little or no alteration or fillings in the Empire Creek intrusive are later and may be related to final cooling or to release of stress by unloading during drilling. Unloading is suggested as an origin for these fractures since at least one of the cores was audibly crackling when it was retrieved at the surface. A significant feature is that the fractures were only partially healed with vein minerals, and that the voids appeared to be linked.

Table 4: Veins and Alteration in the Empire Creek Stock

Core	Depth (m)	Veins	Alteration
5	304- 307	Quartz, orthoclase, sericite or muscovite, fluorite, calcite, pyrite, molybdenite	Plagioclase to sericite kaolinite, montmorillonite. Biotite to chlorite.
6	465- 466	Quartz, pyrite, molybdenite, other sulphides	Plagioclase strongly to kaolinite. Biotite to chlorite.
7	590- 593	Quartz	Plagioclase strongly to kaolinite, montmorillonite. Biotite to chlorite.
8	700- 701	Quartz	As in 7, slightly weaker.
9	848- 849	Quartz, chlorite, pyrite, molybdenite.	Highly altered.
10	1009-1010	Quartz, feldspar.	Highly altered.
11	1163-1166	Quartz	Feldspars strongly to kaolinite. Biotite moderately to chlorite.
12	1297-1300	Quartz, kaolinite	Plagioclase strongly to kaolinite. Orthoclase moderately to kaolinite. Biotite partially to hematite, chlorite.
13	1607-1608	No veins	Plagioclase strongly and orthoclase weakly to clays. Biotite moderately to chlorite.
14	1836-1838	Quartz, orthoclase, plagioclase fluorite, limonite.	Plagioclase highly and orthoclase slightly to clays. Biotite slightly to chlorite.
15	1954-1955	Clay	Plagioclase highly to kaolinite and some montmorillonite. Biotite slightly to chlorite.

Some definitive research in the areas of fractures and alteration in plutonic rocks has recently been reported by Stone and Kamineni[43] and Kamineni and Dugal.[44] Their results provide a useful framework for interpreting the observations at the Marysville heat flow anomaly. In a detailed study of the Eye-Dashwa Lakes pluton in north-western Ontario, Stone and Kamineni[43] noted that most fractures formed during or immediately after pluton solidification. New fractures became smaller and more restricted as cooling progressed. Infilling of these fractures occurred during or immediately after their formation. Some fractures appear to have been sealed by filling materials and then were subsequently sheared and filled by lower temperature materials. The large majority of observed fractures were sealed.

In their study of the Eye-Dashwa Lakes pluton, Kamineni and Dugal[44] showed that pink coloration in the otherwise gray granite was caused by alteration and could be closely correlated with the location and density of fractures. In addition, they showed that a number of physical properties of the rock changed with alteration. Their summary of properties for altered and unaltered rock is reproduced in Table 5.

2. An Hypothesis

Based on the preceding observations, the following model, or hypothesis, is proposed for the Empire Creek stock: Most of the fractures in the stock were formed during and shortly after solidification of the pluton. The fractures were sealed in the late cooling stages by low temperature minerals. It is highly unlikely that the geothermal anomaly is caused by heat associated with the original emplacement of this stock, since the stock is approximately 40 Ma old. Therefore, the heat source came into existence below the area of the heat flow anomaly at some subsequent time and has resulted in hydrothermal groundwater flow through the Empire Creek and Bald Butte stocks. It is not known how long the heat source and related hydrothermal activity have been in existence. The heat source has contributed to the hydrothermal circulation by providing energy to drive convective circulation. The higher temperatures changed the stable mineral assemblages and increased the chemical reaction rates. The effects of these changing conditions and geochemical kinetics are

complex. Dissolution of minerals is initiated, however, minerals may also be precipitated. It appears from the observed large groundwater flows that permeability, at least in some parts of the stock, has been enhanced. In other parts there may also have been a decrease in permeability. It appears that groundwater circulation has altered the rock mass, as indicated by the pink coloration of the rock and by the kaolinization of the plagioclases. The

Table 5: Properties of Unaltered and Altered Rock[44]

Property	Unaltered Rock	Altered Rock
(1) Density (g cm^{-3})	2.65	2.58 - 2.63
(2) Intrinsic velocity (compressional) (km s^{-1})	6.583	6.503
(3) Magnetic susceptibility (S.I.)	20 10^{-3}	5 10^{-3}
(4) Thermal conductivity ($Wm^{-1}K^{-1}$)	3.2	3.6
(5) Mechanical strength	lower	higher
(6) Matrix permeability (μD)		
(a) unconfined	8.38	0.44
(b) confined	1.59	0.15
(7) Porosity (%)	0.40	0.09
(8) Sorption capacity	lower	higher

alteration has probably caused a reduction in the density and magnetic susceptibility of the Empire Creek and Bald Butte stocks, as is suggested by Table 5. It appears that a large volume of rock has been altered, and this may contribute to the negative gravity anomaly and lack of magnetic anomaly over the stocks. The degree of alteration increases with the depth of the borehole, and must continue to a substantial depth if it is the cause of the gravity anomaly. The large degree of alteration suggests that there was an extensive network

of fractures in which the hydrothermal fluids percolated. However, an examination of the core photographs indicates that although veins and fractures are common, they are by no means as pervasive as observed, for example, in the stockwork in porphyritic copper deposits.[52]

A feature of this hypothesis is that the permeability for the convective circulation is controlled predominantly by geochemical factors such as fluid and rock chemistry, temperature, time and pressure. It is not necessary to invoke the creation or growth of fractures by fracture mechanics or thermomechanical means.

Is it possible for dissolution to enhance the permeability of a granite pluton by enlarging fracture apertures? A very simplistic calculation (Appendix B) invoking a number of assumptions and relying on minimal data does not rule out the possibility that under favorable circumstances, fracture apertures could be increased. If we assume that fracture filling material with a dissolution rate constant similar to feldspar is dissolved by circulating water at 85°C for 10,000 years and no other minerals precipitate, fracture apertures could increase 6 mm. This simplistic calculation suggests that the equilibrium geochemistry and the kinetics of reactions in repository host rocks and pore fluids should be examined further. Sophisticated analyses should be completed using sufficient geochemical data to assess whether geochemical alteration could significantly increase groundwater flowrates and, consequently, radionuclide transit times.

If dissolution is taking place, as hypothesized, then deposition must also be occurring somewhere in the groundwater flow system. It is interesting to speculate that the thermal transition zone of Figure 9, as well as the bottom section of the conductive zone, might be due to precipitation decreasing the permeability of the granite stock, and thus, resulting in conductive rather than convective heat transfer.

The porosity of crystalline rocks is caused primarily by fractures, and thus, is relatively small, typically less than one percent. Increases in fracture aperture of the order estimated above will affect the permeability significantly, since permeability is proportional to the cube of the aperture.[39] However, porosity will not be affected significantly. Since the repository will provide thermal energy, groundwater flow rates may be high and transit times for radionuclides to reach the environment could be short.

F. ENVIRONMENTAL EFFECTS

The objective of this chapter is to summarize some of the environmental conditions of the Marysville heat flow anomaly and to assess whether such a heat source causes a deleterious effect on the environment.

Of particular interest is the infra-red aerial survey described in Chapter C, 1.6. No detectable temperature difference occurred at the ground surface, although the temperature of tree canopies over the heat flow anomaly was increased by about 1.5^{o}C. Subsequent ground surveys indicated that this temperature increase had not resulted in any tree diseases or insect infestations.

No other manifestations of the heat flow anomaly, such as hot springs, were observed. In fact, the area was not recognized as being geothermally anomalous until Blackwell carried out a heat flow study in the region.[4] It is clear that the Marysville heat flow anomaly has had a virtually imperceptible effect on the local environment.

An environmental analysis was performed by the Bureau of Land management[45] prior to permitting the drilling for the geothermal project to commence. In addition to studying the effects of the drilling program, the report also provided a description of the existing environment, that is, of the geothermal region. The report describes the geography, land use, plant and animal life,

ecological interrelationships, etc. Absolutely no mention is made of any abnormalities in the region which could be attributed to the enhanced heat flow. By negative inference, it is concluded that a heat flow anomaly of this magnitude will not cause environmental damage.

G. OTHER GEOTHERMAL REGIONS

1. Introduction

This chapter reviews three other geothermal areas: the Coso geothermal area, the Roosevelt Hot Springs thermal area and southwest England. These thermal areas have been selected because they are all associated with granitic terrain. The first two areas, Coso and Roosevelt Hot Springs, have much higher heat flows than the Marysville region, whereas the heat flow in southwest England is less than in the Marysville geothermal area. The three case histories in this chapter are not presented in great detail, but rather, their general descriptions have been included to provide a broader perspective on geothermal areas.

2. Coso Geothermal Area

The Coso geothermal area is a region of hydrothermally altered rock and fumarolic activity located in the Coso Range in southeast California within the Basin and Range physiographic province. It has been comprehensively investigated by the United States Geological Survey and others in an effort to evaluate the geothermal resource potential.[40] The area is of interest since the results of a broad suite of geological and geophysical surveys are available and can be compared to the investigations performed at Marysville.

A thin veneer of basaltic to rhyolitic volcanism covers a basement of pre-Cenozoic plutons and metamorphic rocks. The region has undergone extensional tectonism over the last three to four million years which is still active today. The area is a 'classic' geothermal area in that it has visible

surface manifestations such as fumaroles and hot springs and a very high heat flow of up to 940 mW/m^2 with temperature gradients up to 900°C/km. Geophysical surveys indicate that the area has low electrical resistivity and is associated with seismic ground noise, in contrast to observations at Marysville. The data are consistent with a model in which the thermal energy is supplied by deep circulation of fluids through fractured hot rocks above a relatively small, deep silicic magma reservoir.[40]

3. Roosevelt Hot Springs Thermal Area

The Roosevelt Hot Springs thermal area is located in southwestern Utah within the Basin and Range physiographic province. The thermal area is situated in a Tertiary granite pluton which is partially covered by a veneer of rhyolitic tuffs and domes of age 0.8 to 0.5 Ma. The area has been extensively studied for its geothermal energy resource potential by a group at the University of Utah.[47] As at the Coso area, a broad suite of geological, geophysical and geochemical surveys have been performed. In addition, seven production boreholes have been drilled to depths of about 2 km.

The area is characterized by very high heat flow, up to 1000 mW/m^2 with temperature gradients up to 960°C/km. Alteration is abundant in the pluton and is associated with fractures to a depth of at least 2 km. Major patterns of earthquakes occur 30 km to the east-northeast, but only minor earthquake activity occurs near the Roosevelt Hot Springs area. The heat flow and electrical resistivity data both outline anomalous zones along a system of faults that controls the near-surface fluid flow. The source of heat is interpreted to be the convective circulation of thermal water. The groundwater is a dilute NaCl brine and geothermometer determinations imply source temperatures of about 240 to 285°C.

4. Southwest England

A large, elongated granite batholith of Hercynian age (290 Ma) intrudes older sedimentary rocks to form the spine of southwest England. Heat flow studies by

Tammemagi and Wheildon[48,49] show that the batholith is mildly geothermal with heat flows of about 130 mW/m^2 and temperature gradients of about $40^oC/km$, whereas the surrounding country rock has a normal heat flow of about 70 mW/m^2. The area is characterized by copper and tin mineralizaion and localized areas of intense alteration (kaolinization).[50] Warm springs have been reported in the area and many of the presently operating mines as well as many from the previous century report the flow of warm water ranging in temperature from 24 to 47^oC in their underground workings. The cause of the heat flow anomaly has not been determined, although it is suspected that it is related to hydrothermal convection through fractures in the batholith.

5. Discussion

The geothermal areas which have been described range from very hot (Coso and Roosevelt Hot Springs) to mild (southwest England) with Marysville lying somewhere in between. Heat flows range from 120 to approximately 1000 mW/m^2. The age of the plutons ranges from 10 to 290 Ma. Although varying in intensity, hydrothermal alteration of the rock mass and convective flow of thermal groundwater have been involved in all cases. The information from all four sites is consistent with the hypothesis presented in Chapter E, Section 2.

There is no question that granite plutons can be good conduits for groundwater flow in geothermal conditions. The data from southwest England and Marysville suggest that this may occur even with relatively mild geothermal conditions.

H. DISCUSSION

1. Role of Geoexploration Surveys

A review of the geothermal exploration in the Marysville region provides a valuable insight into the role of geological and geophysical surveys and their varying degrees of usefulness in achieving the required objectives. It is noteworthy that the existence of an extensive circulation system of hot

groundwater in a fracture network had not been predicted, and only came to light because of the deep borehole. It is clear that direct information obtained from boreholes is vital to any exploration program, including the selection and characterization of plutons for a nuclear waste disposal facility. This point is in conflict with the philosophy that drilling should be minimized at any potential repository site since it may compromise the integrity of the site. The level of certainty concerning subsurface conditions in any area is directly related to the number of boreholes. It is the opinion of the authors that a comprehensive drilling program is essential, and that emphasis should be placed on ensuring that the boreholes can be adequately sealed, rather than trying to minimize them. It is also important that the pluton of interest has plentiful surface outcrop. Many of the enigmas of the Marysville study could be resolved if the Empire Creek and Bald Butte stocks were well exposed at ground surface. The preceding points are of such fundamental importance that they should form the cornerstone of any repository site characterization program.

2. Comparison of Marysville and Empire Creek Stocks

An intriguing contrast exists between the Marysville and Empire Creek stocks. The characteristics of the two igneous intrusives are summarized in Table 6. A fundamental question is why the two neighbouring stocks have such contrasting heat flow signatures. It is possible that the Empire Creek stock is intrinsically more permeable than the Marysville stock and, thus, by allowing convective groundwater circulation, has channeled heat from a broad thermal source at depth. It is more likely, however, that the heat source is localized below the Empire Creek stock and has caused the permeability of the stock to increase by the mechanisms outlined in Chapter E. A thorough study of the geological and hydrogeological characteristics of the two stocks might provide information for categorizing plutons with regard to their anticipated behaviour under thermal conditions. This information would be useful for the repository site selection process.

Table 6: A Comparison of the Empire Creek and Marysville Plutons

Property	Empire Creek Stock	Marysville Stock
Age (Ma)	40	79
Rock Type	Granite (prophyry to equi-granular) - 40% quartz; 50% orthoclase; 5% plagioclase; 5% biotite.	Granodiorite
Mineralization	Molybdenum	Gold
Heat Flow	Anomalously high up to 600 mW/m^2 and 240°C/km	Normal, about 80 mW/m^2 and 30°C/km.
Magnetic Field	No anomaly	1600 gamma anomaly
Gravity	Negative anomaly	No anomaly
Alteration	High	?
Structural Conditions	?	?
Electrical Resistivity	High	High

3. Recommendations

There are many uncertainties concerning the Marysville geothermal region, and many studies that could be undertaken to unravel them. A limited number of recommended studies are presented in this section.

More data are required concerning the Empire Creek stock and the heat flow anomaly. The veins, fractures and alteration of the existing core and rock chips should be thoroughly investigated. The data need to be categorized and interpreted to assess the geochemical hypothesis of Chapter E. Additional direct data are also required in the form of a borehole with complete core recovery. Detailed hydrogeological logging of the uncased portion of the deep borehole should be undertaken. Permeabilities, in-situ pressure and water

samples are required. Tests should be undertaken to determine the degree of hydraulic interconnectivity between the deep hole and "slant hole".

Further studies are recommended to characterize the Marysville stock and to compare it to the Empire Creek stock. Structural conditions (i.e. fractures, joints, etc.) need to be determined from surface mapping and from borehole data. A cored borehole would facilitate the study of veins, fracture-coating minerals and rock alteration, as well as allowing subsurface access for comprehensive hydrogeological testing and sampling. It would be of particular interest to investigate the contact between the stocks.

It is felt that further mathematical modelling of the heat transfer processes would be of limited use at this stage and should be deferred until further data are available.

A number of studies can be carried out to assess the geochemical model presented in Chapter E and the brief analysis of Appendix B. Theoretical and laboratory investigations should focus on dissolution kinetics of appropriate fracture filling materials and at relevant temperatures and pressures.

4. Heat and Rock

This case history has shown that an active thermal groundwater circulation system exists within a granitic stock in the Marysville geothermal area. The groundwater appears to be of meteoric origin, is relatively young, and flows with relatively high rates through an extensive fracture network. A geochemical hypothesis has been postulated in which the heat and groundwater cause an enhancement of fracture permeability and alteration of the rock mass. This model is capable of explaining the differences in the gravity, magnetic and heat flow surveys between the Marysville and Empire Creek stocks. A review of three other geothermal areas corroborates that granites can become very permeable when subjected to long term heat, and can support extensive hydrothermal circulation.

Considerable research will be necessary to quantitatively assess whether an irradiated fuel repository, which will generate heat for tens of thousands of years, will cause similar hydrothermal circulation in its surrounding rock mass. However, the maximum temperatures and temperature gradients which are currently being proposed for an irradiated fuel repository are similar to those presently encountered in southwest England and at Marysville (see Figure 11) and suggest that rock mass/hydrogeological behaviour, as outlined above, is a distinct possibility.

This report has shown the importance of studying natural analogues to understand the future behaviour of radioactive waste disposal systems. A process or mechanism has been revealed which has the potential to jeopardize the far-field containment barrier. The significance of this process has not previously been recognized.

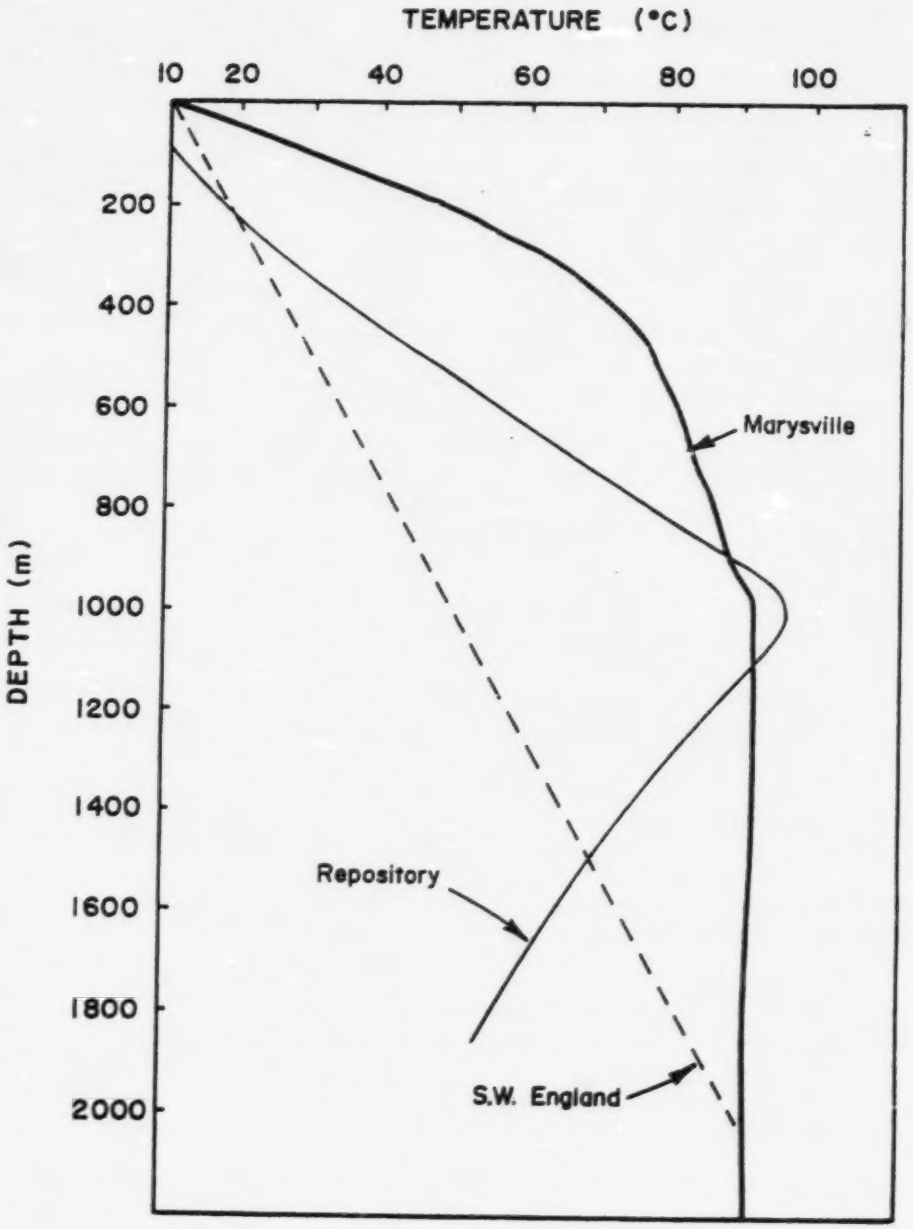

FIGURE 11- COMPARISON OF TEMPERATURE GRADIENTS FOR A CONCEPTUAL REPOSITORY(IN GABBRO AT 10,000 YEARS[1]), THE MARYSVILLE GEOTHERMAL AREA[7], AND SOUTH-WEST ENGLAND[48].

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APPENDIX A

CORE DESCRIPTION

Core 1: 99.1-102 m. Dacite porphyry.

Core 2: 132.9-135.9 m. Empire shale.

Core 3: 177.0-180 m. Empire shale.

Core 4: 280.7-283.8 m. Empire shale and/or Spokane argillite.

Core 5: 303.9-306 m. 3.0 m of core was recovered. The core consists of a very light gray, altered, granite porphyry containing phenocrysts of plagioclase up to 0.6 cm, biotite up to 0.5 cm, quartz up to 1.0 cm, and orthoclase up to 1.4 cm. The rock has approximately 15% orthoclase microperthite, 10% quartz, 2% biotite and 5% plagioclase phenocrysts. The groundmass of the rock in thin section is made up of quartz, orthoclase, plagioclase, biotite, fluorite and pyrite. Plagioclase has been altered to sericite, kaolinite, and montmorillonite, while the biotite has been partially altered to chlorite. Vertical, 35° and 65° veins with alteration zones of up to 3 cm width contain quartz, orthoclase, sericite or muscovite, fluorite, calcite, pyrite and molybdenite. Some horizontal movement is indicated by the horizontal striations or slickensides along fractures. Accessory minerals include zircon and sphene.

Core 6: 464.5-466.3 m. 1.8 m of core was recovered. The core consists of a pinkish gray granite porphyry containing phenocrysts of biotite 0.7 cm, plagioclase 0.7 cm, orthoclase 1.7 cm and quartz 1.0 cm. The rock in hand specimen has approximately 20% quartz, 10% orthoclase, 10% plagioclase and 3% biotite phenocrysts. The groundmass of the rock is composed of quartz, biotite, plagioclase and orthoclase. Plagioclase has been strongly kaolinized, while the orthoclase has only been slightly altered. The biotite has been partially altered to chlorite with some pyrite and other sulphides being located in some of the crystal sites. Vertical, 20° and 60° veins up to 0.4 cm wide are filled with quartz, pyrite, molybdenite and other sulphides.

Core 7: 590.1-593.3 m. 0.2 m of core was recovered. The core consists of a light greenish-gray, altered, granite porphyry containing phenocrysts of biotite (0.6 cm), plagioclase (0.7 cm), orthoclase (1.4 cm) and quartz (0.9 cm). The rock in hand specimen has approximately 40% quartz, 5% plagioclase, 50% orthoclase and 5% altered biotite. The feldspars in the rock have been highly altered to kaolinite, montmorillonite and possibly other clay minerals. The biotite has been altered mainly to chlorite. A vein dipping at 45° approximately 0.5 cm wide contains quartz with altered feldspar and biotite.

Core 8: 699.5-710.0 m. 1.5 m of core was recovered. Core 8 in hand specimen is similar to core 7, but with slightly less feldspar and biotite alteration. The fractures are from 0.5 to 0.6 cm wide and only partially healed with quartz, molybdenite, etc. The voids still seem to be linked along the fracture zones.

Core 9: 848.0-849.2 m. 0.9 m of core was recovered. The core consists of a light gray to light greenish-gray, highly altered granite porphyry containing phenocrysts of biotite (0.6 cm), plagioclase (0.7 cm), orthoclase microperthite (1.4 cm) and quartz (1.3 cm). The relative percentages of the minerals remain th same in thin section as core 7 and 8. The composition of measurable plagioclase is An_5. 55° and 75° veins from 0.2 to 1.0 cm wide in the core contain quartz, chlorite, pyrite and molybdenite, These fractures have been almost totally healed, with some having 1.9 cm alteration zones. Accessory minerals include fluorite, pyrite and zircon.

Core 10: 1009.5 - 1010.7 m. 0.9 m of core was recovered. The core consists of a brecciated, highly altered, light gray granite porphyry containing phenocrysts of biotite (0.9 cm), orthoclase (1.4 cm), plagioclase (0.7 cm) and quartz (1.1 cm). The rock in hand specimen has approximately 25% orthoclase, 20% quartz, less than 5% plagioclase and less than 5% biotite phenocrysts. The groundmass consists of these same minerals. Brecciation fractures have been totally healed by cryptocrystalline quartz and feldspars. Later 10°, 60° and 80° fractures have only been partially healed by cryptocrystalline quartz and other minerals. These fractures contain openings 0.1 to 0.5 cm wide.

Core 11: 1163.4-1165.9 m. 1.6 m of core was recovered. The core consists of a light gray, altered granite porphyry containing phenocrysts of biotite (1.0 cm), plagioclase (0.9 cm), orthoclase (1.3 cm) and quartz (1.1 cm). The rock in hand

specimen has approximately 5% biotite, 50% orthoclase, 5% plagioclase and 40% quartz. The feldspars have been strongly kaolinized, but the biotite has been only moderately altered to chlorite. Veining in the core has mostly a 55° to 75° orientation with the veins being 0.5 to 1.0 cm wide. The veins are filled predominantly with cryptocrystalline quartz and have zones of alteration containing orthoclase and green biotite surrounding them.

Core 12: 1297.2-1299.7 m. 1.7 m of core was recovered. The core consists of a light gray to purplish-gray, altered porphyritic granite containing phenocrysts of biotite (1.0 cm), plagioclase (1.2 cm), orthoclase (1.4 cm) and quartz (1.2 cm). The rock in hand specimen has approximately 5% biotite, 5% plagioclase, 50% orthoclase and 40% quartz. Plagioclase has been strongly kaolinized, while the orthoclase has only been moderately altered. The biotite has been partially altered to hematite, chlorite, etc. Some mineralized veins containing cryptocrystalline quartz and kaolinite are found in the core. Late 85° veins up to 0.3 to 0.5 cm wide contain mylonite zones. Horizontal fractures 3.0 to 5.0 cm apart may be found in a 15 cm section of the core.

Core 13: 1606.3-1608.1 m. 1.0 m of core was recovered. The core consists of a light pink, altered porphyritic granite containing phenocrysts of orthoclase (1.3 cm), plagioclase (0.7 cm) and quartz (0.9 cm). The rock in hand specimen has approximately 5% biotite, less than 5% plagioclase, 50% orthoclase and 45% quartz. The groundmass of the rock in this core is more equigranular with fewer phenocrysts. Plagioclase is highly altered to clay minerals, while the orthoclase has only been slightly altered. The biotite has been moderately altered to chlorite. There are few if any veins in the core, but there are horizontal fractures every 3 cm or closer. The core has also been fractured vertically with little or no veining associated with the fractures. Miarolitic cavities up to 0.3 to 0.5 cm in diameter can be found in the core. (A fine grained granite porphyry sample containing phenocrysts of quartz, biotite and orthoclase and a quartz vein 1.5 cm wide was retrieved at the top of the core. It is not considered to have originated at this depth.)

Core 14: 1835.5-1837.6 m. 1.5 m of core was recovered. The core consists of a dark pink, altered porphyritic granite containing phenocrysts of orthoclase microperthite (1.4 cm), plagioclase (0.8 cm) and quartz (1.0 cm). The rock in thin section has approximately 5% or less biotite, 5% plagioclase, 45% orthoclase

and 45% quartz. The plagioclase is highly altered to clay minerals, while the orthoclase is only slightly altered. The composition of measurable plagioclase in An_{5-7}. The biotite has been slightly altered to chlorite. The groundmass is easy to see in hand specimen and equigranular. Horizontal fractures occur every 8 to 10 cm with little or no alteration along them. 80° fractures 0.2 to 0.3 cm wide contain cryptocrystalline quartz, orthoclase, plagioclase, fluorite and limonite. Accessory minerals include apatite, sericite, zircon, pyrite and hematite. Miarolitic cavities of up to 4 x 1.5 x 1 cm are found in the core (containing euhedral crystals of orthoclase and quartz).

Core 15: 1953.8-1955.0 m. 0.6 cm of core was recovered. The core consists of a pink, altered equigranular granite. The rock in thin section has approximately 5% or less biotite up to 0.9 cm, 10% plagioclase (0.8 cm), 55% orthoclase microperthite (1.2 cm) and 35% quartz (1.0 cm). The plagioclase is less altered in this core than in previous cores, but is still highly altered to kaolinite and lesser amounts of montmorillonite as identified by x-ray diffraction. The composition of measurable plagioclase is An_{5-7}. Orthoclase in the core has only slightly altered to clay. The biotite is still replaced partially by chlorite (brunsvigite). There are some horizontal fractures 8 to 20 cm apart and diagonal fractures with little or no alteration, except for a thin film of clay or a dull appearance along the fractures. Miarolitic cavities can be found in the core with dimensions 1 x 2 cm.

APPENDIX B

ANALYSIS OF FRACTURE APERTURE GROWTH

The objective of this analysis is to assess the potential for kinetic dissolution to enlarge fracture apertures in a thermal environment similar to that which is expected near an irradiated fuel repository. The analysis is simple in approach, has gaps in the input data and makes many assumptions. Nevertheless, it does provide some degree of support for the geochemical hypothesis proposed in Chapter E.

The analysis extrapolates typical linear rate constants for kinetic dissolution of feldspar to elevated temperatures. Assuming a typical density for feldspar, and knowing the number of moles of mineral dissolved per unit surface area per unit time, a growth in crack aperture can be calculated.

Linear rate constants as determined by Busenberg and Clemency[1] for feldspars at 25°C have been used since no data for fracture filling materials or at relevant temperatures could be found.

$$\text{Linear rate constant } (25^{\circ}C) = 3 \times 10^{-16} \text{ (mole/cm}^2\text{/sec)}$$

A rule of thumb in chemistry is that chemical rates increase by two or three for every 10K rise in temperature. Thus,

$$\text{Linear rate constant } (85^{\circ}C) = 200 \times 10^{-16} \text{ (mole/cm}^2\text{/sec)}$$

It is conservatively assumed that one "mole" of feldspar consists of one cation, one atom of Al and one SiO_2 yielding a mole weight of approximately 120 gm. It is also assumed that feldspar has a density of about 2.7 gm/cm^3.

For a fracture aperture to be enlarged by a cm by kinetic dissolution at 85°C over a period of time, t sec, the following relationship holds:

$$a = 2 \times 10^{-12} t$$

where a is in cm and t is in seconds.

For 1000 years, $a = 6 \times 10^{-2}$cm
and at 10,000 years, a = 0.6cm

This calculation indicates that a fracture can open by approximately 0.6 cm by kinetic dissolution over a 10,000 year period. This is a significant increase since the permeability is proportional to the cube of the aperture; it would have a significant influence on groundwater circulation.

The following assumptions and simplifications have been used in the analysis:

(a) it is assumed that rate constants for fracture minerals are similar to those for feldspars,
(b) the rate constant at 25°C was extrapolated to 85°C,
(c) the transient portion of the dissolution process was ignored,
(d) precipitation of solute onto the fracture surface was ignored,
(e) diffusion into rock matrix was ignored,
(f) groundwater chemistry was ignored,
(g) alteration to clays has been ignored.

REFERENCES

1. E. Busenberg and C.V. Clemency, The Dissolution Kinetics of Feldspars at 25°C and 1 atm CO_2 Partial Pressure, Geochemica Cosmochemica Acta, 40, 41-19, 1976.